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**THE PHYSIOLOGICAL COSTS OF WEARING  
RESPIRATORY PROTECTIVE DEVICES**

**A THESIS IN PARTIAL FULFILMENT OF  
THE REQUIREMENTS FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY**

**at**

**MASSEY UNIVERSITY**

**Ian Stewart Laird**

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## ABSTRACT

This thesis is concerned with the use of respiratory protective devices in New Zealand industry and the physiological costs the respirator imposes on the wearer. Two cross sectional surveys of respirator users were undertaken to determine the extent and nature of use or non-use in the working environment and which factors contribute most to non-use. Evidence is presented that indicated that non-use is common (50% of those surveyed) and that difficulty breathing, thermal discomfort and difficulty communicating and seeing were all important reasons for non-use. In addition, it was found that respirators are worn for extended lengths of time and that many users believe that their work when wearing a respirator was physically demanding. Evidence is presented that this is not the case.

The physical characteristics of respiratory protection in terms of resistance to airflow, weights and dead space volumes, were measured in a selection of commonly used respirators in NZ industry. It was evident that most pressure-flow relationships were below recommended limits for inspiratory and expiratory resistances and that some masks in particular, offered little external resistance to breathing.

The physiological consequences of wearing respirators was examined in a series of studies measuring relationships in heart rate, oxygen consumption, ventilation, facial skin temperatures and perceived exertion, with and with-out subjects wearing respirators and at differing levels of external work. It was found that the respirator imposed little physiological strain (in terms of heart rate, gas exchange and minute ventilation), but that psycho-physiological sensations (perceived difficulty breathing and rated perceived exertion) increased significantly. In addition, increases in facial skin temperatures, particularly the lip temperature under the mask when worn, caused a sensation of thermal discomfort that may be the predominant cue that influences reasons for non-use. Finally, the incongruence between physiological and psycho-physiological measures of distress was clearly demonstrated in this thesis. It is apparent that not only is a respirator a complex device, but the micro-climate it produces on the skin surface and the effect this has on an individuals' perception of discomfort, is also enigmatic.

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## ABBREVIATIONS

### Breathing Pattern

$T_i$	=	inspiratory time, seconds
$T_e$	=	expiratory time, seconds
$f$	=	breathing frequency, breaths per minute
$V_t$	=	tidal volume, litres
$\dot{V}_{min}$	=	pulmonary ventilation, litres per minute

### Gas Exchange and Heart Rate

$\dot{V}_{O_2}$	=	oxygen consumption, litres per minute, millilitres per minute per kilogram
$\dot{V}_{CO_2}$	=	the production of carbon dioxide, litres per minute, millilitres per minute per kilogram
$R$	=	respiratory exchange ratio
$\dot{V}_{O_2 \max}$	=	maximal oxygen consumption, litres per minute, millilitres per minute per kilogram
$\% \dot{V}_{O_2 \max}$	=	$(\dot{V}_{O_2 \text{ at work}} / \dot{V}_{O_2 \max} \times 100)$ relative aerobic strain, %
$\%RW$	=	percentage relative workload $(\text{mean } \dot{V}_{O_2} / \dot{V}_{O_2 \max} \times 100)$ , %
$HR$	=	heart rate, beats per minute
$HR_{\max}$	=	maximal heart rate, beats per minute
$\%HRR$	=	percentage heart rate range $(HR_{\text{work}} - HR_{\text{rest}} / HR_{\max} - HR_{\text{rest}}) \times 100$ , %

### Others

s.d.	=	standard deviation
NS	=	not significant
$T_s$	=	temperature (skin), °C
$T_r$	=	temperature (rectal), °C
$T_d$	=	temperature (dry bulb), °C
$T_{wb}$	=	temperature (wet bulb), °C

%RH	=	relative humidity, %
RPE	=	rated perceived exertion
PDB	=	perceived difficulty breathing
W	=	Watts
W/m <sup>2</sup>	=	Watts per metre squared
SCBA	=	self contained breathing apparatus
P.N.	=	Palmerston North
S.I.	=	South Island
NIOSH	=	National Institute of Occupational Safety and Health
ECG	=	electrocardiogram
CNS	=	central nervous system
MANOVA	=	analysis of variance
SAMI	=	socially acceptable monitoring instrument

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## **CHAPTER 1**

### **1.0 INTRODUCTION**

Respiratory protective equipment (respirators) are used primarily to protect individuals from inhalation of airborne contaminants in a wide variety of work environments and situations. They are used when other preventive controls such as extraction or dilution of an airborne hazard using a ventilation system or the isolation and enclosure of the process generating the hazard are insufficient or impracticable. The types of chemical hazards most commonly identified that require the use of respiratory protection include dusts, vapours, mists, gases and fumes. In addition, environments that are deficient in oxygen may also require the use of respiratory equipment (Department of Health, 1984).

Respiratory protective devices are an important part of occupational health and safety practice in New Zealand and are worn by a significant part of the workforce that have exposure to airborne contaminants. Yet, reports often occur in the news media, of individuals being seriously affected by exposure to toxic or harmful substances, some fatally, as a result of their failing to wear a respirator at a critical time. In addition, the National Poisons and Hazardous Chemicals Information Centre has reported an increase in poisoning notifications due to industrial and agricultural chemicals over recent years (Department of Labour, 1992). It is, therefore, essential to identify the reasons, perceived or otherwise, by the user for respirator non-use and attempt to establish the physiological and psychological factors that result in non-use. This research aims to contribute to this area of knowledge.

### **1.1 Historical Background**

The concept of 'the respirator' is not new. Documented evidence on the use of devices to protect the respiratory tract has been found from Roman times. Plinius Secundus (A.D. 23-79) stated - " persons polishing cinnabar in workshops tie on their

face loose masks of bladderskin, to prevent their inhaling the dust in breathing, which is very pernicious and nevertheless to allow them to see over the bladders" (C Plinius Secundus, *Historis Naturalis Lib.* 33 sec 40).

During the Middle Ages the use of respiratory protection was reported in connection with a number of industrial processes, including mining for raw metals such as lead, mercury, phosphorous and zinc (Patty, 1978; Ballantyne and Schwabe, 1981). However, it was not until the 19th century that the technical development of air-purifying devices began. Early components of respirators included " animal bladders or crude rags wrapped around the nose and mouth, to full face masks made of glass with air-inlets covered with particulate filters" (Patty, 1978). Masks were produced for fire fighters that had combined aerosol filters and vapour sorbents (Patty, 1978). The U.K. Factories (Prevention of Lead Poisoning) Act 1883, required white-lead factories to conform to prescribed standards with regard to air ventilation, lavatories, baths for women, mealrooms, protective clothing and respirators. This was one of the first Acts of Parliament to specifically mention the need to wear respiratory protection. Sir Thomas Legge (1863-1932), the first Medical Inspector of Factories, had significant insight to problems faced by workers. Through his own researches and through his aphorisms for preventing occupational disease, he identified the following:-

"Axiom 5. Examples of Influence - Useful to a point, but not completely effective - which are not external, but depend on the will or whim of the worker to use them, are respirators, gloves, goggles, washing conveniences and waterproof sand-paper " (Legge, 1934).

The mining industries of the United States and the United Kingdom have played a major role in the development and certification of approved types of respirators from that time (Hyatt, 1958; Fleming, 1958; Jordan, 1958; NIOSH, 1987). The U.S. Bureau of Mines gave its first approvals of oxygen breathing apparatus in 1918 and gradually extended its approval to include all types of respirators (Jordan, 1958; NIOSH, 1987). However, the major technical developments were launched with the introduction of toxic gases to the battle fields of the First World War (Patty, 1978; Ballantyne and

Schwabe, 1981). Adequate protection for front line troops was deemed essential during the frequent and extensive gas attacks. The military's interest in the design and performance of respiratory protection began to increase dramatically from the First World War (Hyatt, 1958; Fleming, 1958; West, 1958). In tracing the development of respiratory protective equipment, it is also evident that major improvements for 'civilian' respirators were the result of developments of respiratory protection for warfare (Jordan, 1958; Jette *et al*, 1990). The following statement appears in the American Standards Association Safety Code for the Protection of Heads, Eyes and Respiratory Organs, No. Z2-1938:-

"The development of gas masks was carried on intensively during the war and at its conclusion the results were applied to masks for industrial purposes".

The statement refers to World War One, but it is also perfectly true regarding developments that occurred as a result of World War Two. Military interest in respirator protection is still evident to the present day (Jette *et al*, 1990).

With the coming of the Second World War and the increased complexity of respiratory equipment requirements further advances in the performance and design of respiratory protection occurred (Jordan, 1958). These developments covered a wide range of activities, as the three illustrations that follow demonstrate:-

- \* Research undertaken at the Los Alamos Research Laboratories in New Mexico, was of particular importance in determining respirator efficiencies to very fine radioactive particulate material (Hyatt, 1958; Jordan, 1958).
- \* In response to a requirement in the U.S. Army Ordinance Corps, the U.S. Army Chemical Corps was requested to develop a paint spray respirator for use in Ordinance shops where Ordinance vehicles were renovated and painted, since no available commercial respirators were acceptable to the armed forces.
- \* In 1948 the Chemical Corps was authorised by the Research and Development Division, Department of Army, to develop a low cost non-combat protective mask for use by civilian employees and dependents of U.S. Armed Forces personnel at U.S. military installations on foreign soil (Fleming, 1958; West, 1958).

The range of respiratory protection currently available to industry is extensive (Department of Health, 1984; National Institute for Occupational Safety and Health, 1986). However, major technical improvements in respirator design and performance have not been as dramatic since hostilities ceased. The basic design and characteristics of respiratory protection have been effectively unchanged from the last World War until the present day. Jordan in 1958 commented:-

"The depressing aspect of the matter is that, as matters stand today-some twelve years since the war, industrial workers can expect little improvement in their respiratory protective devices until after the next war. - Not a single soldier owes his life or health to the proper use of the gas mask in the last war. On the other hand, the total economic loss and number of personal tragedies brought about by the death and impaired health of industrial workers breathing harmful industrial substances is overwhelming and impossible of calculation."

He continues:-

"Obviously, this loss and suffering did not result from the use of improper respirators; the point is that the task of protecting workers from inhalation hazards requires the daily use of a great number of respirators and this demand justifies our best research efforts.

The manufacturers of respiratory protective equipment have had ample opportunity to develop a suitable research program in the field. The fact that their personnel have not contributed to the literature or to major developments in the field is evidence that the research activities which manufacturers are capable of supporting are not adequate."

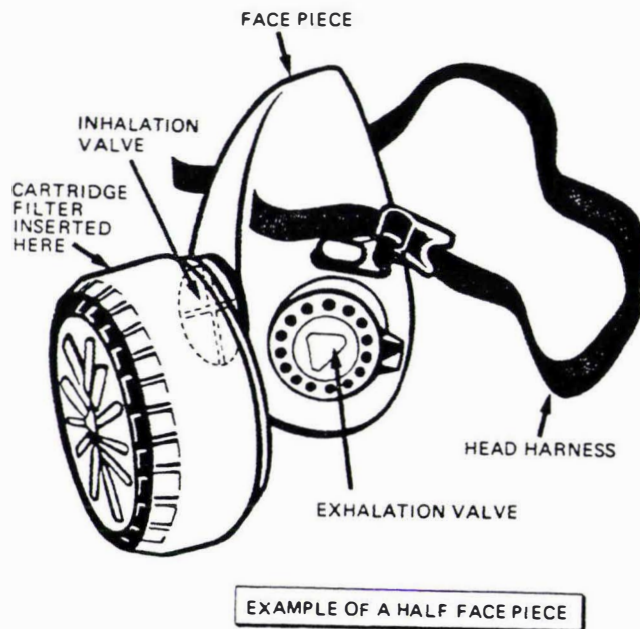
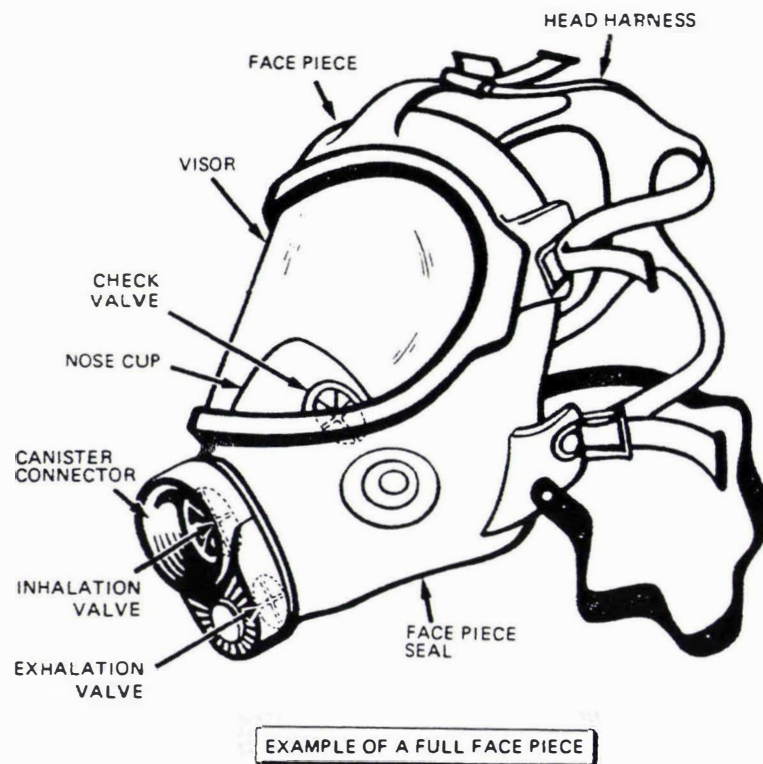
The sentiments expressed by Jordan in 1958 would be disputed today by many respirator manufacturers. A number of companies are actively engaged in research into respirator performance and design (e.g. refer Safeguard, April 1992). However, it is apparent to the author that some of Jordans' concerns, expressed nearly forty years ago, may still be valid today.

## 1.2 The Anatomy of the Respirator

Respirators are usually classified into three major categories: air - purifying devices, supplied - air devices and self - contained breathing apparatus (Department of Health, 1984; Lundin and Colton, 1988). The air pressures within the components of these systems usually define the type of respirator. Air purifying respirators rely on a negative pressure system for contaminant removal i.e. air must be drawn through the filter under negative pressure. The wearer initiates inspiration by creating a negative pressure in the mask to overcome the resistance of the filter, that must be maintained throughout the duration of inspiration. This mechanism adds to the negative airway pressure required for inspiration. Additional expiratory effort is also required to open the expiratory port in the air-purifying devices (Ballantyne and Schwabe, 1981). There are however, devices that have technical features between this classification e.g. an air-purifying respirator that has a source of 'powered' or 'forced' air supply and effectively functions as a supplied air device.

Supplied-air devices utilise an air compressor to feed uncontaminated air to a hood, helmet or mask. In the case of an air-supplied mask, the wearer initiates inspiration by creating a negative pressure sufficient to open the inspiratory valve to enable the compressed air into the face mask. In the case of hoods and helmets, a continuous positive pressure air flow is supplied through the system and normal inspiratory pressures can be maintained (Lundin and Colton, 1988).

Self contained breathing apparatus (SCBA), is a compressed air closed circuit device. The elements of the unit include a compressed air cylinder, an airline hose connected to an air-flow regulator and a face mask. In a similar way to supplied -air respirators, the wearer initiates inspiration by creating a negative pressure sufficient to open the inspiratory valve to enable the compressed air, from the cylinder, into the face mask. The devices are suitable for short term work and in emergency use. They let the wearer work without the restriction of a hose or airline in an atmosphere that is heavily contaminated and/or deficient in oxygen (Department of Health, 1984; Lundin and Colton, 1988). The main limitations of these devices are their size, the limited



**Fig. 1.1 Diagrams of air-purifying respirators commonly worn in industrial environments.** The facemask and head harness mechanisms, cartridge and canister orientation and valve configurations are illustrated.(Source Respirators and Breathing Apparatus, Department of Health, 1984).

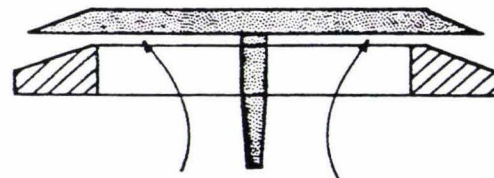
capacity of the air cylinder and their weight (refer section 1.5.2).

Of the three differing types of devices, air-purifying respirators have been shown to be the most frequently and extensively used in industry (Aucoin, 1975; Louhevaara, 1984; Louhevaara *et al*, 1985; Lundin and Colton, 1988; Bellin and Hinds, 1990; Jones, 1991). This thesis is primarily concerned with air-purifying respiratory protection.

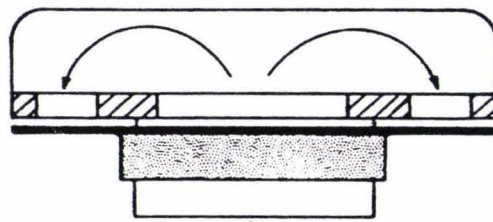
### 1.2.1 Air Purifying Respirators

Air purifying respirators incorporate either mechanical or chemical means of removing the contaminants from the air. This is accomplished by air being drawn in through a filter system (usually a canister or cartridge filter mounted on an inhalation port) and out through an exhalation valve, or by inhalation and exhalation through a mask made of semi-permeable material that removes contaminants (e.g. disposable dust masks). The essential features of an air-purifying respirator are (Fig. 1.1):

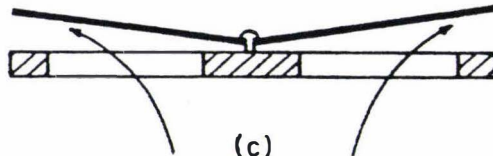
1. The facepiece (often referred to as 'masks' or 'facemasks'). These are usually moulded from impermeable materials and cover the nose and mouth or the whole face. The face piece is the foundation upon which the filtration, air exchange and harnessing systems are mounted. Some devices have incorporated visors to protect eyes and facial areas from exposure to contaminants (Fig.1.1)
2. Adjustable headstraps attached to the facepiece of respirator hold it in close contact with the facial contours. The straps are made from elasticised material, rubber, plastic, or a combination of these.
3. A system of inspiratory and expiratory valves.  
The valves are in four configurations (adapted from Burgess and Anderson, 1967) (Fig. 1.2).
  - (i) Mushroom type valve - has a moulded rubber diaphragm with a centre stem inserted in a locating hole in a cross bracket in a valve body. The valve body is usually made of rubber or plastic and has a contoured



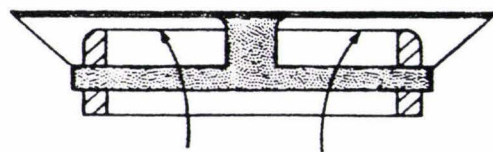
(a)



(b)



(c)



(d)

**Fig. 1.2** Diagrams illustrating the major expiratory valve types. Four valve types can be seen: (a) Mushroom-type valve, (b) Annular-type valve, (c) Flap-type valve, (d) Poppet-type valve. (Source Burgess and Anderson, 1967).



peripheral seat. Expiratory air-flow lifts the edges of the disk from the seat. As air-flow increases, the displacement of the disk increases. The valve may be provided with a cover. The mushroom-type valve is most widely used on both half and full facepieces.

- (ii) Annular type valve - where the rubber diaphragm is in the form of an inverted top hat, whose crown covers a circular opening. The brim of the top hat acts as the diaphragm sealing a series of ports in the cap overhang. Airflow lifts the brim and initiates the flow of expired air.
- (iii) Flap type valve - consists of a single sheet of rubber which is lifted from a port in the valve seat when expiration occurs. Reversal of flow causes closure of the port. The valve or diaphragm is made in either a leaf or disk configuration.
- (iv) Poppet type valve - has a unique moulded type rubber diaphragm. A disk which establishes a seal at the valve seat is attached to a retaining band with four hinges. The hinges permit the plane displacement of the disk away from the seat with airflow and reseating when flow is stopped.

#### 4. Filters

As indicated previously, the filter may be designed to remove particles, gases, vapours, mists, or any combination of these. Particulate filters draw contaminated air through a fibrous material to trap and thus remove the particulate matter from the inspired air. The factors which determine the efficiency of the filter include the air velocity, the nature of the filter material and the nature, shape and size of the particles (Ballantyne and Schwabe, 1981; Bellin and Hinds, 1990). The constituents of filters designed for particulate material vary according to the type and degree of protection required (NIOSH, 1976; Patty, 1978; Ballantyne and Schwabe, 1981). High efficiency dust, fume and mist filters have a pleated sheet of filter material, often glass fibre paper,

in the filter holder (Lundin and Colton, 1988). Pleating decreases the flow velocity, improves particle loading capacity and decreases resistance to breathing (NIOSH, 1976). Other types of dust respirators employ a disc of compressed fibre. A specific type of particle removing filter is the disposable dust-mask type respirator, in which the filter material forms the major or whole portion of the respirator. Many disposable dust-mask type respirators are fitted with exhalation valves in an attempt to enhance breathing efficiency (NIOSH, 1976; Ballantyne and Schwabe, 1981).

Gas and vapour filters are designed for removal of specific materials by methods described under the term 'sorption' (Ballantyne and Schwabe, 1981; Lundin and Colton, 1988). The sorbent, in the form of granular porous material, is contained in canisters or cartridges. Canisters are holders containing the air-purifying sorbent and are connected directly or by a flexible hose to the respirator facepiece. A canister may also incorporate a filter to remove particulates. An inhalation valve in the canister and a non-return exhalation valve in the facepiece control the direction of air flow in most models. Cartridges are smaller containers that are directly attached to the facepiece. Since cartridges contain lesser volumes of sorbent they have shorter functional lives (NIOSH, 1976; Ballantyne and Schwabe, 1981) and are generally used in circumstances where the contaminant concentrations are comparatively low. Cartridges may also contain pre-filters to remove coarse particulate material (Ballantyne and Schwabe, 1981; Department of Health, 1984; Lundin and Colton, 1988).

The mechanism of sorption of materials is by adsorption (physical attraction, retention of material in the pores of the sorbent), absorption (chemical attraction) or catalysis (the catalyst increases the rate of the chemical reaction, which in turn promotes filtration). In contrast with particulate filters, as the dynamic sorptive capacity becomes saturated the efficiency of the air-purification decreases and ultimately contaminant begins to pass into the facepiece. This has been referred to as breakthrough (NIOSH, 1976;

Ballantyne and Schwabe, 1981; Department of Health, 1984).

As Crockford (1980) described, it is obvious that most air-purifying equipment cannot provide complete protection against all environmental contaminants. Some dust will penetrate the filter, some gas will leak through exhalation valves. It is important to know how much protection is provided by the device and the concept of the 'Nominal Protection Factor' (NPF) of the respirator is currently used to indicate this. The respirator only acts as an attenuator of the contaminant due to the fact that leaks are going to be present. The nominal protection factor is therefore the concentration of the contaminant on the outside of the respirator over the concentration of the contaminant on the inside. Most commercially available air purifying respirators give an indication of the protection factors achievable with their promotional material and are within a relatively narrow range within one order of magnitude (NPF range, 5-50). Self contained breathing apparatus and supplied-air respirators have significantly higher protection factors (NPF range, 10-10,000) (NIOSH, 1976; Lundin and Colton, 1988), due to the closed circuit source of air to the facemask.

### 1.3 The Use of Respiratory Protection

Anecdotal evidence from a number of sources suggest that there is a reluctance to wear respiratory protective devices in the work place (Anon, 1970; Harris, 1974; Aucoin, 1975; Beckett and Billings, 1985). In 1970 a survey was undertaken among insulation workers in the United States to assess their experiences in wearing air-purifying respirators (Anon, 1970). The major reasons cited for not wearing respiratory protection were discomfort (37%) and interference with breathing (21%). The term 'discomfort' referred to in the survey however, was not detailed. One study reported that respirators are worn for only 20 -30% of the work time that they should be worn (Aucoin, 1975). Despite a series of studies going back over 40 years (see Silverman, *et al*, 1951; Raven, Dodson and Davis, 1979; Louhevaara, 1984; Harber *et al*, 1991 for reviews) it is not known why this behaviour occurs. Three opinions prevail: Firstly, that the problem is mainly psychological (Epstein *et al*, 1982; Morgan, 1983; White *et al*, 1989; Wilson *et al*, 1989). Secondly, that the sensation of wearing a face

mask creates, as yet undescribed, physiological responses (Craig, Blevins and Cummings, 1970), possibly involving skin temperature (Nielsen *et al*, 1987; Gwosdow *et al*, 1989; DuBois *et al*, 1990). Thirdly, that the added resistance to airflow and respiratory 'dead space' create a sensation of dyspnea (James, 1976; Harber *et al*, 1984; Louhevaara *et al*, 1985; Harber *et al*, 1989).

The need for further field studies in areas of respirator acceptability and use have been regarded as important by many authors (Corn, 1980; Louhevaara, 1984; Beckett and Billings, 1985) but it is only recently that studies have sought the opinions of respirator wearers on issues of respirator performance, comfort and acceptability (Morgan, 1983; Harber *et al*, 1984; Beckett and Billings, 1985; Morgan and Raven, 1985; White *et al*, 1989; Harber *et al*, 1991). This study attempts to document respirator users perceptions and attitudes and based on these findings investigate the physiological and psychological factors that relate to acceptability of the devices.

#### 1.4 Physiological Measures

The term physiological stress is often used to describe the demands of external loads on the body's systems (Astrand and Rodahl, 1986; Wilson and Corlett, 1990). This load may be environmental, physical, emotional or cognitive. This 'stress' elicits a 'strain' in the individual as an attempt to maintain homeostasis. Homeostatic limits are specific to the individual depending on that individuals capabilities and limitations. These limits are not a point but rather a range within which the body system can regulate and maintain itself without any tissue damage. These limits have been shown not to be static but are dynamic in the sense that they can change over time due to a variety of reasons, for example physical training (Astrand and Rodahl, 1986). Physiological strain is used to describe the response in the human body and traditionally involves measurements of variables of the cardiovascular and pulmonary systems (Kilbom, 1990). The assessment of these stresses and strains are important components of ergonomics and work physiology (Wilson and Corlett, 1990). Physical stress can be accurately predicted and measured using a variety of physical and physiological methods (Kilbom, 1990). The measurement of oxygen uptake during

work aims at assessing the physical stress during a work operation. Physiological strain is often measured by recording cardiac frequency (heart rate response) and thermo-regulatory response of individual to the stress (core and skin temperature changes).

Early studies on respiratory protective devices were largely concerned with the evaluation of the physical characteristics of the respirator (air-flow resistances) and the additional physiological demand a respirator imposes on an individual (Silverman *et al*, 1943; Silverman *et al*, 1945; Silverman *et al*, 1951; Jordan, 1958; Cooper, 1960; Burgess and Anderson, 1967). Later, studies concentrated on the effects that wearing the devices had on the individual in terms of changes to the pattern of breathing and gas exchange (Hermansen *et al*, 1972; Dressendorfer *et al*, 1977; Harber *et al*, 1982; Harber *et al*, 1984; Louhevaara *et al*, 1984; Louhevaara *et al*, 1985; Louhevaara, 1986; Jette *et al*, 1990; Jones, 1991). According to reviews on the physiological (James, 1976; Raven *et al*, 1979; Louhevaara, 1984; Jones, 1991) and psychological (Morgan, 1983) aspects of the use of respirators, the most important factors affecting physical work performance include additional inspiratory and/or expiratory breathing resistance, the external dead space of the device and the weight of the equipment.

The stress imposed by external work, which affects a respirator wearer, depends on such factors as dynamic and static work load, environmental conditions, work-rest regimen and the psychosocial demands of the work involved (Silverman *et al*, 1951; Raven *et al*, 1979; Louhevaara, 1984; Louhevaara, 1986). The wearer's strain is the total response to the combined effects of a respirator's physical characteristics (i.e respirator size, weight and inhalation/exhalation characteristics) and the environmental stress factors of the work. The effect of both of these are, in turn, influenced by individual characteristics (including age, sex, weight and fitness) (Louhevaara, 1986). The response (strain) can be assessed by the measurement of alterations to physiological variables (heart rate, gas exchange, patterns of breathing) and psychological variables (perceptions of discomfort, exertion and breathing difficulties) (Refer Figure 1.3).

### 1.3.1 Cardiovascular Strain

As early as 1957 LeBlanc reported that since the main factors in physical work are the supply of oxygen to the muscles and the dissipation of heat produced and both depend on - "the ability of the circulatory system to adapt itself to body requirements and since heart rate is directly effected by these circulatory changes", heart rate may be used as a valid measure of load (strain).

In order to meet these demands the circulation can increase the transporting capacity\* by a factor of 100 within a few minutes after the onset of exercise. This is achieved by (i) the distribution of more blood to exercising muscles, (ii) a more efficient uptake of oxygen and excretion of carbon dioxide and (iii) increasing the total blood flow, by increasing the cardiac stroke volume and heart rate (Kilbom, 1990; Guyton, 1991).

The continuous measurement of heart rate during work is a common method used to evaluate cardiovascular strain (Astrand and Rodahl, 1977; Kilbom, 1990). Although heart rate increases during both static and dynamic exercise, during heat exposure and as an effect of psychological stress (Astrand and Rodahl, 1986; Kilbom, 1990; Guyton, 1991; Jones, 1991; Fox *et al*, 1993), heart rate increase is an unspecific cardiovascular strain response and the interpretation of heart rate recordings must always be made against a background knowledge of the circumstances of the recording. Other factors that can influence heart rate include tobacco smoking, medication, ongoing infections, noise exposure and certain beverages (Astrand and Rodahl, 1977; Kilbom 1990; Jones, 1991; Fox *et al*, 1993).

Many studies report minimal, if any, effects on heart rate by the use of air purifying respirators (Thompson and Sharkey, 1966; Chatterjee, 1969; Epstein *et al*, 1982; Harper *et al*, 1982; Harber *et al*, 1984; Verstappen *et al*, 1986; NIOSH, 1987; Harber *et al*, 1988; Jette *et al*, 1990). Others have shown a modest increase in heart rate (Hermansen *et al*, 1972; Dressendorfer *et al*, 1977; James *et al*, 1984; Louhevaara and Tuomi, 1984; Louhevaara *et al*, 1985; Jones, 1991).

\* (of O<sub>2</sub> to muscle)

Dressendorfer *et al* (1977) and Harber *et al* (1982) found that heart rate tended to increase with higher inspiratory breathing resistances.

Explanations for the increase in cardiac frequency suggested by these authors included (i) increased chemoreceptor or baroreceptor activity caused by changes in alveolar ventilation and intrathoracic pressure (Hermansen *et al*, 1972), (ii) increases in heart rate due to anxiety related to dyspnea (Harper, 1984) and (iii) thermal stress and an increase in the breathing rate that may represent an attempt by the body to dissipate heat (Neilsen *et al*, 1987; Hodous *et al*, 1989; DuBois *et al*, 1990; Jones, 1991)

Jones (1991), in reviewing cardiorespiratory response to air-purifying respirator use suggested explanations for an increase in heart rate may be due to increased cardiac demands caused by the increased work of breathing. This explanation is important in examining the 'physiological cost' of wearing the devices and was first examined by Silverman *et al*, (1951). This author measured the relationships between air-flow resistances in respirators and key physiological responses including heart rate, oxygen consumption and pattern of breathing. Silverman *et al*, (1951) found that air flow curves obtained on the subjects at various work rates vary in rate and amplitude with the work rate and that heart rates ranged from 78-178 b/min. The results of these early studies have largely been confirmed by subsequent authors (see reviews by Raven *et al*, 1979; Louhevaara, 1984).

#### 1.4.2 Physical Work Capacity

The ability of any individual to perform physical work is best evaluated through measurements of the maximum aerobic power, measured as the highest uptake of oxygen per minute ( $\text{Vo}_2 \text{ max}$ ) that can be achieved during dynamic exercise. The rationale for measuring oxygen uptake is that the amount of oxygen consumed during aerobic exercise is directly proportional to the amount of energy produced within the body (Astrand and Rodahl, 1986; Grandjean, 1988; Fox *et al*, 1993). Thus, oxygen uptake is an indirect measure of the demands on work output, i.e. it is a measure of physical stress. Nonetheless there are important exceptions such as physical work in

hot environments, tasks with a large static component and activities which demand a large proportion of anaerobic metabolism (Astrand and Rodahl, 1986; Kilbom, 1990; Fox *et al*, 1993).

The assessment of physical workload is accomplished either by measuring the oxygen uptake during the actual performance of the work operation, or by indirect estimation of the oxygen uptake on the basis of the work heart rate recorded during the work in question (Astrand and Rodahl, 1986; Fox *et al*, 1993). The validity of using oxygen uptake as a basis for measuring energy expenditure has been well established (Astrand and Rodahl, 1986).

Since for a given individual during work, there is generally a linear relationship between oxygen uptake and heart rate, heart rate may, under certain standardised conditions, be used to estimate work load (Astrand and Rodahl, 1986). That is (i) if the work load - heart rate relationship has been established for the individual in question and (ii) providing the same muscle groups are engaged in the work in both cases and (iii) providing environmental and psychological stressors are equivalent (Astrand and Rodahl, 1977; Kilbom, 1990).

Despite these constraints, heart rate is frequently used as an index of strain in the workplace (Kilbom, 1990). This is usually accomplished by the use of miniature battery operated recorders that can monitor heart rates continuously. The recorded heart rate coupled with activity sampling observations show the extent of strain on the individual. The recorded heart rates may then be compared to the individual's heart rate recorded during increasing external work on a cycle ergometer and converted into the approximate oxygen uptake (Astrand, 1967; Astrand *et al*, 1973; Fordham *et al*, 1978; Goldsmith *et al*, 1978; Saha, 1978; Astrand and Rodahl, 1986; Vitalis *et al*, 1994).

In addition, other indices of strain in physical work activities include percentage of maximal heart rate (%HRmax), percentage heart rate range (%HRR) and the metabolic Equivalent (MET). Maximal heart rate (HRmax) refers to the highest cardiac



frequency attainable by an individual during exhaustive external work and is mainly influenced by age (Jones, 1988). Percent HRmax (%HRmax) is correspondingly, a percentage value of the HRmax and is a relative measure of the physical cost of work. Similarly, percent heart rate range (%HRR) is a relative measure of the product of the heart rates at work and at rest in comparison to the maximal heart rate. The term MET is an acronym for 'Metabolic Equivalent' and is defined as a standard quantity of oxygen required for the maintenance of life, on a per kilogram body weight basis, per minute under quiet, resting conditions.

#### 1.4.3 Gas Exchange

Another variable used to measure energy cost is gas exchange (Astrand and Rodahl, 1986; Kilbom, 1990). One study proposed that the energy cost of breathing is increased by respirator usage (Morgan, 1983). However, there is little clear cut evidence for this. In fact, several groups have recorded a fall in oxygen consumption during short term, submaximal exercise periods (Silverman *et al*, 1951; Thompson and Sharkey, 1966) possibly linked to an increased oxygen debt (Raven *et al*, 1979). This oxygen debt could have masked the additional energy cost of breathing through the respirator (Raven *et al*, 1979; Louhevaara, 1984). Oxygen uptake during recovery from an exercise period (and hence oxygen debt) has been shown to be directly dependent on the resistance of the respirator (Thompson and Sharkey, 1966; Louhevaara, 1984).

At submaximal exercise levels oxygen consumption and the production of carbon dioxide has been shown to remain almost unchanged up to an exercise level of 75-80% of the maximal oxygen consumption when compared to the reference values (Hermansen, 1972; Harber *et al*, 1984; Louhevaara *et al*, 1984; Jette *et al*, 1990). The use of air filtering devices has been shown to induce hypoventilation and the retention of carbon dioxide at heavy exercise levels (in excess of 80% maximal oxygen consumption) (Hermansen, 1972; Lerman *et al*, 1983; Louhevaara *et al*, 1984).

During maximal exercise, when the subjects were tested to exhaustion, the use of an

air filtering respirator reduced minute ventilation by 30-45% and oxygen consumption by 14-21% (Hermansen *et al*, 1972; Lerman *et al*, 1983).

As Louhevaara (1984) observed:

" the face mask of the self-contained breathing apparatus is technically similar to the face mask of an air-line apparatus, but the air-containers carried in the former may weigh 15-16 kg and this extra weight is a crucial factor that impairs physical work performance".

Most subjects studied by Louhevaara (1984) were firefighters, whose oxygen consumption whilst wearing respiratory protection often exceeded 2.0 l/min. in emergency situations. The review recommends the use of self contained breathing apparatus only for individuals whose maximal oxygen consumption is at least 3.0 l/min. In addition, as age-induced decline in maximal oxygen consumption is inevitable, effective physical training is necessary to maintain the high physical work capacity required for the use of the apparatus. The review cites experiments in which a self contained breathing apparatus was used with and without a face mask. The extra weight of the air-containers was found to cause almost all the additional physiological strain measured during submaximal exercise (Raven *et al*, 1977; Louhevaara *et al*, 1984; Steinhäus *et al*, 1984). However, with lighter apparatus, designed for use in escape manoeuvres (3.4 kg), it was concluded that the physiological differences detected during submaximal exercise were small (Louhevaara, 1984).

Conversely, supplied-air apparatus appear to have much in common with air-purifying respirators. Breathing resistance and external dead space have been shown to effect work performance, but the additional weights of the devices are not a major contributing factor. Louhevaara (1984) comments that the new models of supplied-air apparatus in particular, induce little detectable physiological strain on individuals at submaximal and maximal levels of exercise.

#### 1.4.4 Pattern of Breathing

Many studies have shown a decreased breathing frequency (Gee *et al*, 1968; Hermansen *et al*, 1972; Harber *et al*, 1982; Steinhaus *et al*, 1984) and an unaltered or slightly decreased minute ventilation, associated with negative pressure respirator use (Hermansen *et al*, 1972; Flook and Kelman, 1973; Dressendorfer *et al*, 1977; Gothe *et al*, 1980; Harber *et al*, 1982; Louhevaara *et al*, 1985; Babb *et al*, 1989). Other studies have shown no effect on minute ventilation (Harber *et al*, 1984; Louhevaara and Tuomi, 1984).

It has been shown that during submaximal exercise added inspiratory breathing resistance decreased breathing frequency, prolonging the inspiratory time of young subjects (Gee *et al*, 1968; Flook and Kelman, 1973; Harber *et al*, 1982). The subjects' tidal volumes remained almost unchanged resulting in a decreased minute ventilation. Love *et al*, (1977) also examined the patterns of breathing in older subjects (over 40 yrs) and found that although breathing frequency was unchanged, tidal volume decreased, resulting in a reduced minute ventilation.

Increased inspiratory breathing resistance during submaximal and, particularly, maximal exercise hinders ventilation and results in hypoventilation and the retention of carbon dioxide (Flook and Kelman, 1973; Dressendorfer *et al*, 1977). It has been suggested that the different breathing patterns of subjects, coupled with considerable interindividual variations may produce unpredictable changes in gas exchange at light and moderate exercise levels (Louhevaara, 1984).

At submaximal and near maximal exercise levels the primary effect of added expiratory breathing resistance (0.5 kPa at an airflow of 2.0 l/s) was to decrease tidal volume, which led to a decrease in the minute ventilation and to hypoventilation (Gee *et al*, 1968; Flook and Kelman, 1973; Dressendorfer *et al*, 1977).

Studies that have evaluated the effects of adding dead air space have shown changes in patterns of breathing, presumably to overcome the effects of the dead air space with

its resultant increase in alveolar carbon dioxide (Louhevaara, 1984). Frequently an increase in tidal volume is seen without any significant change in respiratory rate (Stannard and Russ, 1948; Harber *et al*, 1988; White *et al*, 1989). With large additions of dead air space (>300 ml), the frequency of breathing may actually decrease as tidal volume is increased (Jones *et al*, 1971; Harber *et al*, 1988). Relatively small amounts of dead space (60 ml) have been shown to increase both tidal volume and minute ventilation in one study (Sackner *et al*, 1980).

Thus it would appear that for any level of minute ventilation through a respirator, some optimal combination of tidal volume and breathing frequency is selected. The addition of large volumes of dead space increases ventilatory requirements, which leads to an increase in tidal volume (Louhevaara *et al*, 1984; Steinhaus *et al*, 1984). With small additions of dead space, however, the option of increasing frequency of breathing might offer the advantage of increased heat dissipation via the airways (Raven *et al*, 1979; Louhevaara, 1984), although this option seems inappropriate as heat dissipation through panting does not increase the alveolar ventilation more than is required for control of the blood gases, because each breath is extremely shallow and most of the air that enters the alveoli is dead space air (Guyton, 1991).

#### 1.4.5 Thermal Stress

An individual gains and losses heat through convection, conduction, radiation and evaporation. The heat balance equation derived from this relationship has been well documented (Goldsmith, 1967; Guyton, 1991; Fox *et al*, 1993). The interactions of the various components of the heat exchange system maintain homeostasis and allows heat production to balance heat loss.

An important measure of physiological strain is deep body - or core temperature. Core temperature increases during exercise, since all of the energy is converted to heat. Heat production is one of the principle by products of metabolism. The rate of heat production is dependant on (i) the basal rate of metabolism of all cells in the tissue; (ii) extra rate of metabolism caused by muscle activity; (iii) extra metabolism

caused by the effects of sympathetic stimulation of the cells; and (iv) extra metabolism caused by increased temperature of the cells (Guyton, 1991; Fox *et al*, 1993). Deep body temperature is adjusted in relation to the relative workload and although this adjustment is slow (at least 30 min) it is highly accurate.

Most of the heat produced during exercise in the tissues, is generated in the deep organs, especially the liver, the brain, the heart and the skeletal muscles (Guyton, 1991). This heat is transferred from the deeper organs and tissues to the skin, where it is dissipated to the air and other surroundings. The rate of heat loss is determined almost entirely by two factors; (i) how rapidly heat can be conducted from the core to the skin and (ii) how rapidly heat can be transferred from the skin to the surroundings (Guyton, 1991; Fox *et al*, 1993). Physical work in hot environments imposes large stresses on an individual's ability to maintain this balance (Kilbom, 1990). If uptake and production of heat cannot be balanced by heat dissipation, deep body temperature increases producing heat exhaustion and heat stroke (Guyton, 1991; Fox *et al*, 1993).

Measurements of deep body temperature are traditionally made with sensors in the rectum, as the rectal temperature is a representative indicator of physiological strain (Astrand and Rodahl, 1986). The temperature in the rectum varies with the distance from the anus, it is customarily measured at a depth of 5 to 8 cm. The rectal temperature in a resting individual has been found to be:

"slightly higher than arterial blood, about the same as liver temperature , but slightly lower than that part of the brain where the thermal regulatory centre is located" (Astrand and Rodahl, 1986).

No single core temperature level can be considered normal, for measurements on many normal persons have shown a range of temperatures (from less than 36°C to over 37.5°C) (Guyton, 1991).

The skin temperature, in contrast to the core temperature, rises and falls with the temperature of the surroundings. This is important to the transfer of heat from the tissues to the surrounding environment (Kilbom, 1990; Guyton, 1991; Fox *et al*, 1993).

Skin temperature measurements are made by placing thermal sensors on the skin at certain locations (trunk, thighs, arms, face, hands, feet). Mean skin temperatures can be calculated by assigning certain factors to each of the measurements in proportion to the fraction of the total skin surface area represented (Astrand and Rodahl, 1986).

The measurement of skin temperature is dependant on surrounding air temperature. Of interest to this study is the inter-relation of conductive, convective and evaporative heat loss as a consequence of respirator use (Nielsen *et al*, 1987).

Of the physiological parameters most responsive to change, the thermal effects of respirator use play an important part in device acceptability. Recently, DuBois *et al*, (1990), studied the effect of three differing types of half-facepiece respirators on facial discomfort, thermal sensation and sweating. These authors concluded that thermal conditions of the face contributed to and may possibly dominate, the discomfort of wearing air purifying respiratory protective devices.

Thermal stress or discomfort during respirator use has been investigated by a number of authors (Nielsen *et al*, 1987; Gwosdow *et al*, 1989; Hodous *et al*, 1989; White *et al*, 1989; DuBois *et al*, 1990; Jones, 1991). The results of these studies demonstrated that facial skin temperatures in excess of 34.5°C inside the mask are considered by the wearers to be warm and uncomfortable. Skin temperatures within this range appear to be critical in sensations of discomfort. A number of studies have attempted to quantify subjective assessments of discomfort associated with a range of ambient air and skin temperatures whilst wearing a respirator (Nielsen *et al*, 1987; White *et al*, 1989; Gwosdow *et al*, 1989, DuBois *et al*, 1990). One psychological study indicated that the most 'bothersome' aspect of wearing respiratory protective equipment was excessive heat inside the devices (Hodous *et al*, 1989).

Jones (1991) found an increase in mean lip temperature under a disposable dust mask of 7.5°C, which is considerably higher than the values recorded by DuBois *et al*, (1990) (2.1°C mean increase in skin temperature after 30 minutes use for a comparable type porous dust mask). The study by Jones (1991), does not cite the work of DuBois

*et al.*, (1990) and, therefore, no explanations are given for the discrepancy in the facial temperatures they observed. Ambient environmental temperatures and relative humidities were not reported in either paper, which makes comparison of experimental conditions difficult. Since these two studies (DuBois *et al.*, 1990; Jones, 1991) constitute the total published data on the effects of respiratory protective devices on facial skin temperature, the data is incomplete with regard to environmental conditions. As these studies do not consider the psychological effects of this thermal stimulus, further study seems appropriate.

As air-purifying respirators use negative pressures to draw air through filters, heat and water vapour delivered by expired air also affect the temperature and humidity of the face. This is significant in light of earlier studies (Louhevaara and Tuomi, 1984; Louhevaara *et al.*, 1985; Louhevaara *et al.*, 1986) which considered air-supplied and self contained breathing apparatus. These devices have the additional component of a forced, or demand fed flow of air over the face during the respiratory cycle which may, in fact, dissipate facial heat.

In addition to thermal sensations of respirator use, DuBois *et al.*, (1990), measured facial heat flow or flux of subjects both before and during wearing a respirator. They reported that the normal heat flux per unit area of the bare face of  $104 \text{ W/m}^2$ , is double that of the rest of the body, which is approximately  $50 \text{ W/m}^2$ . The heat flux diminished when the face was covered by a porous mask (3M 9913 Dust-Mist mask), which caused an increase in the temperature of the skin under the mask. The authors found that heat flux was unaltered when wearing the cotton/ aluminium mask, due to the mask shell (aluminium) being an effective heat conductor.

### 1.5 **Psycho-physiological Measures**

In addition to physiological measures of strain, indices have been developed that inter-relate physical work load and perceptions of exertion. The most widely used of these is the Rated Perceived Exertion (RPE) scale developed by Borg (1962). The scale is often used to supplement physiological measurements during exercise testing and

provides additional information about subjective responses from subjects. The Borg scale has become a well established instrument to test perceived exertion during dynamic physical work (see reviews by Pandolf and Noble, 1973; Ljunggren, 1986). Many studies have demonstrated close correlations between RPE scores and heart rate and other indicators of physiological strain (see reviews by Fleishman *et al*, 1984; Ljunggren, 1986). In addition, studies have also found close correlations between RPE and parameters of stress (work load) (Borg, 1970; Pandolf and Noble, 1973; Stamford and Noble, 1974).

A number of supplementary psychophysical scales have been developed to rate individual sensations of a variety of psychological variables including trait anxiety, respiratory distress and dyspnea (see review by Morgan and Raven, 1985). Morgan and Raven (1985) attempted to quantify respiratory distress by developing a seven point psychophysical category scale. This scale (the perceived difficulty breathing scale, PDB) is a visual analogue scale that combines numbers with verbal descriptions of the perceptions experienced by the subject. These descriptions range from breathing easily, to extreme difficulty breathing. Respiratory distress is then determined by the rating indicated by the subject. The perceived difficulty breathing scale was used in the present study as the measure most preferred of those published in the literature as it (i) provided a simple evaluation of breathing distress, (ii) the scale was easy to administer and (iii) it enabled comparison with earlier results by Morgan and Raven (1985) would be appropriate for this study.

## 1.6 Theoretical Framework for the Thesis

A comprehensive review of the physiological costs of wearing respiratory protective devices was undertaken by Louhevaara in 1984. This review considered air-purifying devices, air-line apparatus and self-contained breathing apparatus. He concluded that:-

1. The additional breathing resistances and external dead spaces of modern-day respirators are low, but that resistances may increase over time if the equipment is not maintained adequately.
2. All types of respirators alter the user's natural breathing pattern and cause at

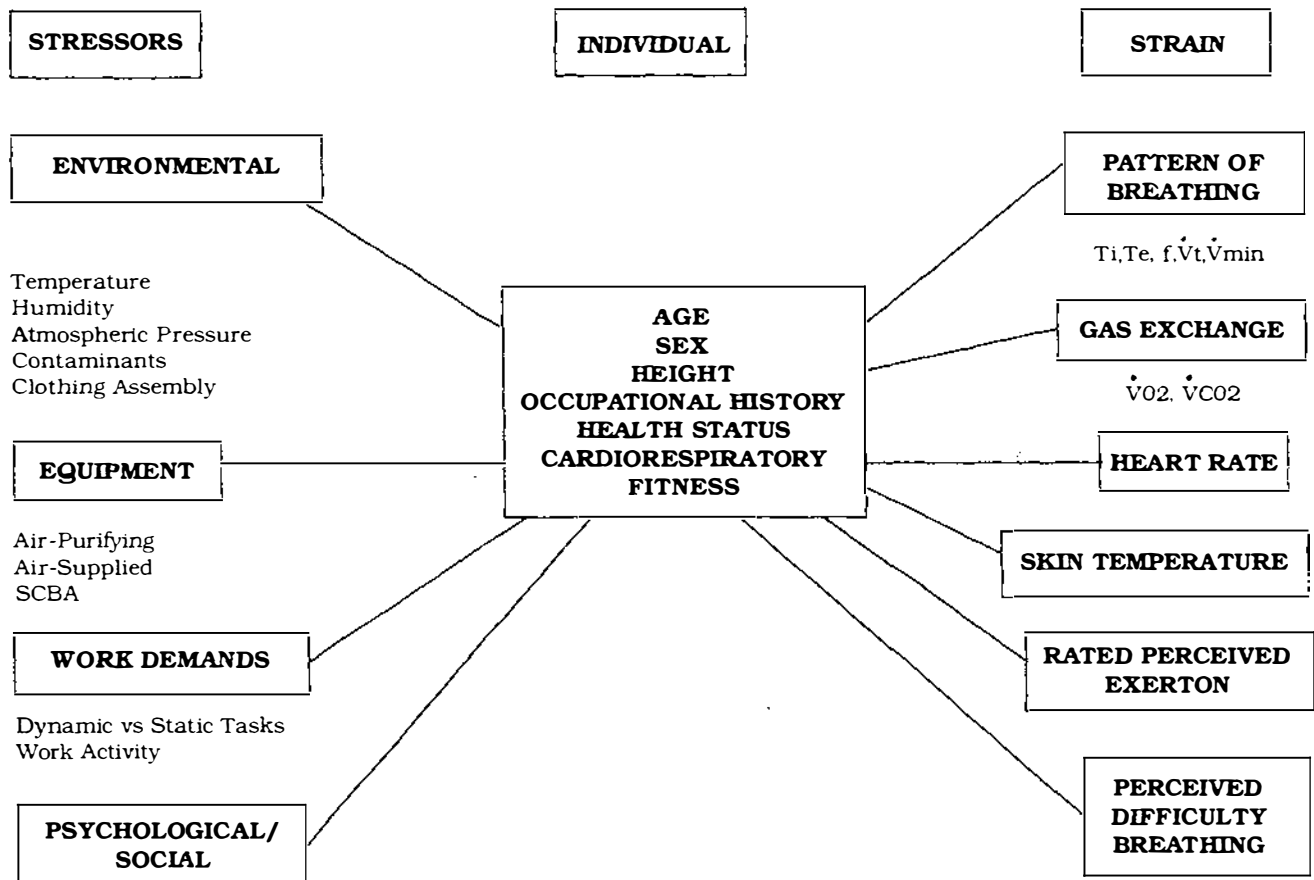


least subjective sensations of discomfort.

3. Although only slight changes in gas-exchange and heart rate may be noticeable, at submaximal work rates hypoventilation and the retention of carbon dioxide may occur.
4. The undesirable effects of respirators become accentuated during heavy physical work.
5. Accurate recommendations for the use of filtering devices or air-line apparatus cannot be given because experiments of long duration have not been carried out. Few studies have been done on female subjects or with subjects whose physical work capacity has been lowered by illness or age.
6. Very limited information is available about the physical demands of industrial jobs that require respiratory protection.

It is evident from the above and the discussion in the preceding sections that a number of factors influence the decision of whether or not to wear a respirator. It appears that wearing a respirator in a work environment imposes a 'strain' on the wearer that is a complex combination of physical, psychometric, physiological and psychological stresses (Louhevaara, 1986).

With these variables in mind, this thesis centres around the examination of the physiological and psycho-physiological consequences of wearing a respirator. A framework is proposed (Figure 1.3) that interrelates these factors. It is an adaptation of the stress-strain analysis of the problem developed by Selye (1950) and modified by Rutenfranz *et al* (1976) and Louhevaara (1985). Essentially, the framework describes the interaction between a range of *stressors* imposed on an individual wearing a respirator and the individuals' physiological characteristics. This result is a *strain*, which is measured by a variety of standard physiological parameters (Fig. 1.3). As discussed in the earlier section (section 1.5) stressors include physical environmental conditions, the physical characteristics of the equipment, the work demands and psychological and social stresses. Measures of an individuals stress and strain respirator use include changes in pattern of breathing ( $T_i$ ,  $T_e$ ,  $f$ ,  $\dot{V}_t$  and  $\dot{V}_{min}$ ), gas exchange ( $\dot{V}_{O_2}$  and  $\dot{V}_{CO_2}$ ) and heart rate (HR).



**Fig. 1.3 Theoretical framework for the study of the physiological costs of wearing respiratory devices.** The framework is a modified stimulus-response model after, Selye (1950), Rutenfranz (1976) and Louhevaara (1985).

In addition to the physiological measures of strain (minute ventilation, gas exchange, heart rate), it was considered important to also include other responses to external stressors, including facial skin temperature and psycho-physiological measures including rated perceived exertion (RPE) and perceived difficulty breathing (PDB), as the physical and psychological factors in work performance operate reciprocally in cueing muscular and cardiovascular effort in relation to feelings of workload, exertion and fatigue (Fleishman *et al*, 1984).

## 1.7 Aim of the Study

The principal aim of this study, is to investigate the physiological consequences of wearing an air-purifying respirator on an individual and to determine the influence these have on the acceptability of such devices.

The research involves a series of inter-related studies which attempt to:

- (i) describe the attitudes, perceptions and behaviour of respirator users;
- (ii) examine the physical characteristics of commonly used respirators;
- (iii) evaluate the physiological strain of respirator use, both in laboratory and industrial environments.

In addition, the study will examine the extent to which 'local' factors i.e. skin sensations, versus 'central' factors i.e. sensations primarily associated with the pulmonary system, may be influential in perceptions of respirator acceptability.

To achieve these aims, four complimentary sets of studies have been undertaken, each with their own specific objectives.

1. Survey of Respirator Usage.

To identify the range of respiratory protective devices worn in a selection of New Zealand industries, the extent of their use and the reasons for use or non-use of the devices.

2. A Study of the Physical Characteristics of the Respirators.

To quantify the resistance to airflow and dead space characteristics of a range of respirators commonly used in New Zealand industry.

3. A Study of the Additional Physiological Cost of Wearing a Respirator.

To measure the additional physiological 'cost' of a respirator at differing levels of external work and alterations to skin temperature and rated perceived exertion (RPE) whilst wearing respirators.

#### 4. Work Environment Study

To determine the level of work activity normally experienced by individuals that are required to wear respirators and how wearing respirators effects the strain of doing the tasks required.

The thesis is structured correspondingly under nine chapters. After a brief introduction in the first chapter, the second chapter reports on studies involving the attitudes, perceptions and behaviour of the users of respiratory protection in New Zealand industry. This is achieved by a cross-sectional survey of respirator users in a selection of industries where respirators are worn.

The third chapter describes a series of laboratory studies that assess the physical characteristics of respirators, particularly in terms of breathing resistances.

The fourth chapter is concerned with the measurement of the additional physiological strain of wearing an air-purifying respirator.

The fifth and sixth chapters examine the effect of respirator use on skin temperature and perceived exertion.

The seventh chapter describes a series of field studies undertaken in work environments to determine the cardiorespiratory strain involved in jobs that require the regular use of an air-filtering device.

The eighth chapter is a general discussion of the results obtained and their implications for respirator users, designers and manufacturers and finally (chapter nine) offers conclusions and suggests directions for future research.

## CHAPTER 2

### 2.0 A SURVEY ON THE USE AND NON-USE OF RESPIRATORY PROTECTIVE EQUIPMENT IN WORKPLACES IN NEW ZEALAND

#### 2.1 Introduction

Very little information is available on the frequency and extent of respirator use in industry in New Zealand or elsewhere. In 1970 a survey was undertaken among insulation workers in the United States to assess their experiences in wearing air-purifying respirators (Anon, 1970). The major reasons cited for not wearing respiratory protection were discomfort (37%) and interference with breathing (21%). The term 'discomfort' referred to in the survey however, was not detailed. As a result a new disposable type face mask was developed and tested. Harris (1974), reported on the use of respirators in coal mining operations in the United States. This field survey examined the length of time the devices were used, their acceptability and problems associated with their use. These problems included breathing difficulties and physical discomfort, which was described in terms of sweat and heat build up under the mask.

In 1977 the United Kingdom National Coal Board assessed the frequency of respirator use by miners (National Coal Board, Annual Report 1976/1977). This study investigated the number of days on which respirators were carried (and presumed used). Patterns of use within shifts were determined by monitoring respirator carriers and recording dust concentrations during the time the respirator was worn in the shift. It was found that carriers on average wore their respirator for 21% of the shift and obtained, assuming 85% overall efficiency (in terms of protection factor) for the respirator, on average a 41% reduction in exposure.

The need for further field studies in areas of respirator acceptability and use have been cited as important by many authors (Corn, 1980; Louhevaara, 1984; Beckett and Billings, 1985) but little recent evidence in the literature indicates that this has been

undertaken. The early studies of respirator use describe subjective assessments of wearer behaviour (Harris 1974; Aucoin, 1975) and provide little evidence of physical or psychological factors associated with tolerance.

The present study was undertaken, to identify the types of respirators worn, the type of work undertaken and the frequency of use (and perceived reasons for use or non-use) of respirators in a sample of industries in two provincial areas (Palmerston North and Horowhenua). A second study was also undertaken in a large manufacturing plant in New Zealand.

The industrial environments of Palmerston North and Horowhenua are primarily described as being service industries for the urban and rural communities surrounding them (NZ Yearbook, 1992). A range of light industry provides a variety of occupational groups in which exposure to airborne contaminants frequently occurs. These include agricultural and chemical spraying, carpentry and joinery factories, chemical process plants, rubber industry plants and engineering workshops which involve welding. This is in contrast to the large manufacturing site investigated in this study in the South Island which has, as its principal activity, the smelting and casting of primary aluminium. The process involves the electrolytic reduction of alumina dissolved in a molten bath of cryolite. Carbon anodes are immersed in the bath which is contained in a carbon lined cell acting as the cathode. The molten aluminium collects as a layer at the bottom of the cell from which it is periodically syphoned. The cryolite bath is gradually lost from the reduction cell through absorption into the lining materials, electrolysis and vapourisation. This loss of fluorides represents the major portion of emissions from an aluminium smelter. In addition, due to the nature of the process, the thermal heat load on individuals working in close proximity to the smelting pots can be extreme. These conditions (where ambient temperatures are high), would likely accentuate the thermal discomfort features of respiratory protection (New Zealand Aluminium Smelters Ltd, 1989).

## 2.2 Materials and Methods

### 2.2.1 Survey of Workplaces in the Palmerston North and Horowhenua Region.

#### Survey Design

A self-administered questionnaire ( Appendix 1) was used to collect information on respirator use. The questionnaire was designed to obtain information on those using respirators in a defined geographical location. Table 2.1 summarises the information sought in the questionnaire with the relevant question numbers.

**Table 2.1 Information sought in the respirator usage questionnaire.** Eight categories of information were sought.

<u>Information sought</u>	<u>Relevant Questions in questionnaire</u>
(1) The types of hazards users of respirators are commonly exposed to.	1, 2
(2) The reasons for wearing the respirator	3
(3) Knowledge of the consequences of exposure to the hazard	4
(4) The type(s) and model(s) of respirators most commonly used	5, 6
(5) A description of the type of work undertaken when wearing the respirator	7
(6) The length of time the respirator is worn during a normal shift	8, 9
(7) The perceived reasons for use and non-use of the respirator	10, 11, 12, 13, 14
(8) The extent of information and training given to respirator users on using, fitting and maintaining the respirator	15, 16, 17

The survey design had to take into account the wide variety of work activities where respirators were worn and the range of devices used. As a consequence, a multi-stage sampling strategy was used. The questionnaire was pretested to determine the adequacy of the sampling strategy and appropriateness of the specific questions. This was undertaken by approaching three organisations (target population), whose employees were known to be using respiratory equipment (n=20, pretest sample population) and identifying through the managers/supervisors, those staff that wore respirators. The questionnaire was then distributed to the employees, who completed them and then commented on the appropriateness of the questions and the ease of questionnaire completion. Ten percent of the pretest sample found difficulty understanding some specific questions, the remainder (90%) found no difficulties with the questionnaire. The questionnaire was subsequently amended in the light of the comments received. The survey design and methodology was reviewed and approved by the Massey University Human Ethics Committee. The major issues of concern centred around the confidentiality and anonymity of respondents replies.

The questionnaire was also evaluated by the assessment committee of the Medical Research Council of New Zealand on behalf of the Accident Compensation Corporation. Issues raised by this committee included minor alterations to question structure and format. Their major concern was that the questionnaire was too technical for a postal survey. Subsequent amendments to the wording overcame this concern and the questionnaire was approved by this authority.

The initial target population was individuals using respirators in various organisations within the Palmerston North city area and in the Horowhenua area where horticulture is the predominant industry. The sample population were respirator users from industries and work premises identified from the database of registered premises (as defined by the Factories and Commercial Premises Act (1981)). These were obtained from the local office of the Department of Labour, Occupational Safety and Health Service.



The survey technique involved identifying first, the industries where respirators would likely be used, secondly the premise or factory within those industry groups and thirdly the respirator users within those premises or factories. This involved personal contact with each manager of the organisations identified to determine the number of staff that wore respiratory protection. The questionnaire was distributed to the identified respirator users by the plant or production manager of the company selected. Completed questionnaires were returned anonymously to Massey University. These were coded and statistical analyses were performed using an established statistical analysis system (SAS Institute, Inc., Cary, N.C.). Simple frequency analyses and cross tabulations were undertaken on the data.

Identified non-respondents were followed-up to improve response rates. This involved providing a follow up letter and a further questionnaire for those identified users who had not responded within four weeks of the commencement of the survey. This was achieved with the assistance of the manager or supervisor of the organisation concerned. For surveys of this nature a response rate in excess of 70% has been reported as the minimum acceptable (Brownlee, 1957; Donald, 1969; Babbie, 1973).

### 2.2.2 Survey of a Manufacturing Site in the South Island

The same questionnaire was distributed to employees of the large manufacturing site by The Occupational Health Unit of The Company. Respirator users were identified by the staff of the Unit and the questionnaire (Appendix 1) was distributed at appropriate times during each shift break. Completed questionnaires were collected by the staff of The Occupational Health Unit of the company and forwarded to Massey University for coding and analysis. However, the respondents were given the right to send the completed questionnaires directly to Massey University. Statistical analyses were performed, as in the previous survey, using the Statistical Analysis System (SAS Institute, Inc., Cary, N.C.). Identified non-respondents were followed-up by Occupational Health Staff of the company to improve response rates. Similar ethical issues were identified in this survey and the procedures previously used were adopted to ensure confidentiality and anonymity were maintained.

**Table 2.2 List of industries approached and the numbers responding to the questionnaire (Palmerston North Area).**

	<u>Individuals Approached</u>	<u>Number Responded</u>
Agricultural Spraying	25	16
Chemical Handling	14	6
Fire Fighting	8	8
Fumigation	7	4
Chemical Mixing	14	8
Packing/ Bagging	12	4
Sanding/ Grinding	20	14
Paint Spraying	18	12
Electroplating	3	1
Tyre Buffing	5	1
Welding	4	1
Not adequately described	10	6
Total	140	81

**Table 2.3 Age Characteristics of Respondents (Palmerston North Area).**

<u>Age Group (Yrs)</u>	<u>Number of Respondents<sup>#</sup></u>	<u>%<sup>*</sup></u>
<20	2	82.8
20 - 29	29	40.8
30 - 39	20	28.2
40 - 49	9	12.7
50>	11	15.5
Total	71	100.0

\* Excluding 15 non-response questionnaires.

# Ten respondents failed to detail age.

## 2.3 Results

The questionnaires provided data on:

- (i) The types of hazards encountered.
- (ii) The types of respiratory protection used for these hazards.
- (iii) The extent of use.
- (iv) The reasons for use or non-use of the devices.

There were several common features between the two surveys. Air-purifying respirators were the most common form of respiratory protection worn and exposure to dusts was the hazard most commonly experienced. A large proportion of respirator users (ranges from 20% to 40%) were required to wear the devices for extended periods of time (over 4 hours) and even larger proportion (ranges from 50% to 60%) removed the devices before the work that requires its' use was complete.

### 2.3.1 Palmerston North and Horowhenua Region Survey

The types of industries approached and the numbers responding from each are listed in Table 2.2. The largest proportion of respirator users (20%) came from spraying agricultural chemicals, primarily in horticultural work. Sanding and grinding activities accounted for 17% of users and paint spraying 15% of users. The remainder undertook a variety of tasks.

Of 140 respirator users approached, ninety six replied to the questionnaire (69% response rate). Of these 15 returned the questionnaire indicating that they were supposed to wear respirators at work but, in fact, did not. No reasons were given in the follow up to account for this. Of the completed questionnaires (n=81, 72 males, 9 females), Table 2.3 shows the age characteristics of the respondents. Seventy percent of the respondents were comparably young (below 40 years). The majority of the subjects were of European background (90%), the remaining 10% were of Maori or Pacific Island descent.

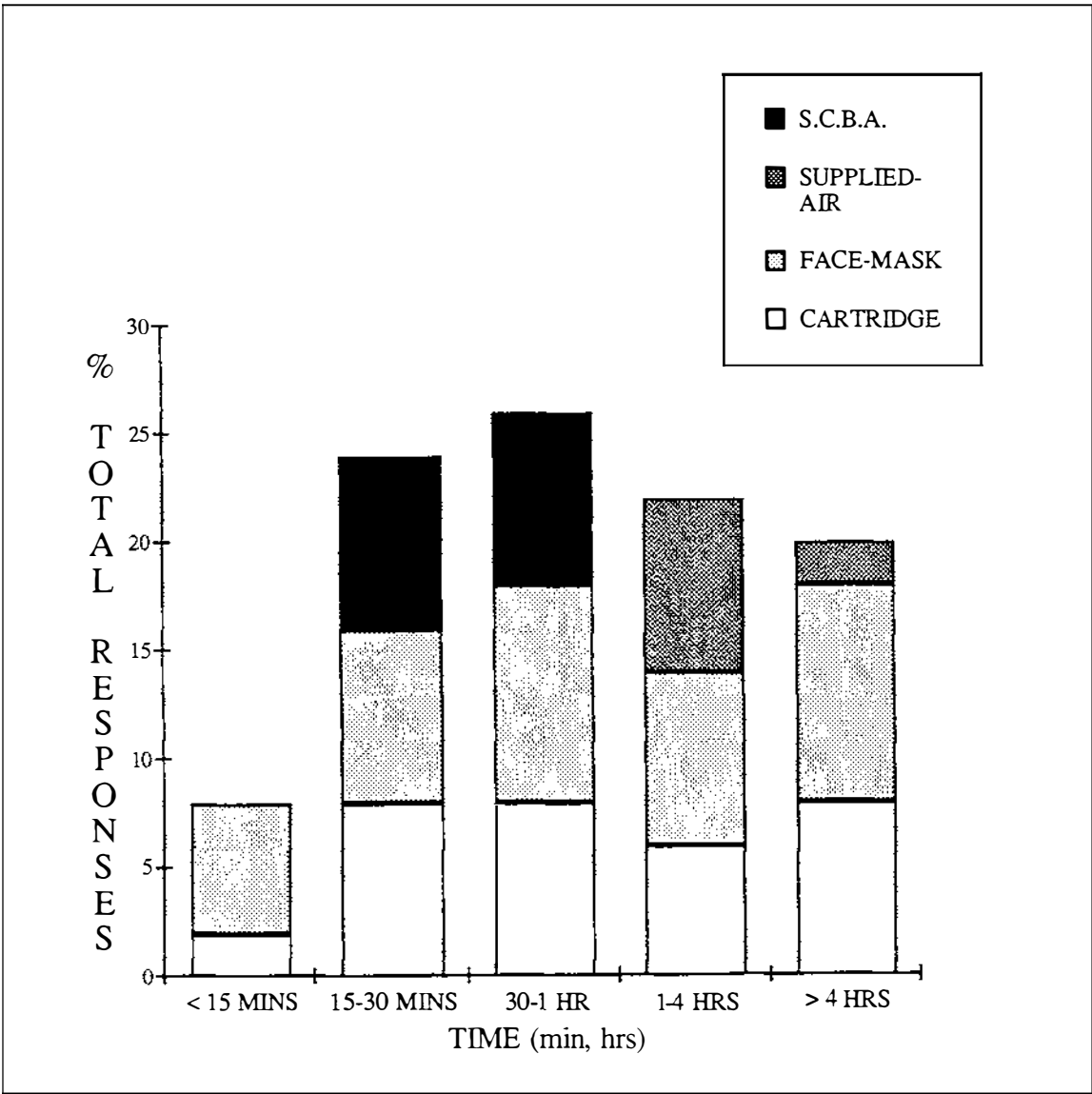
Respondents indicated they were exposed to dusts (40%), vapours and mists (33%) and gases and fumes (26%) and that they wore appropriate respiratory protection for these hazards. The most common reason given for wearing the respirator was as a precaution against a perceived hazard (63%) compared to 29% who wore a respirator because of a management requirement to do so.

Knowledge of the health effects of exposure to the hazards was varied. Most respondents indicated that exposure affected the respiratory system (42%) or other parts of the body (11%) or that the effects were generally harmful (27%). Nearly 10% of the respondents were unaware or unsure of the nature of the effects of exposure or the period of time for which exposure was hazardous. Forty four percent of the subjects considered that exposure would be hazardous over a short period of time (hours or days) rather than a long period (months or years).

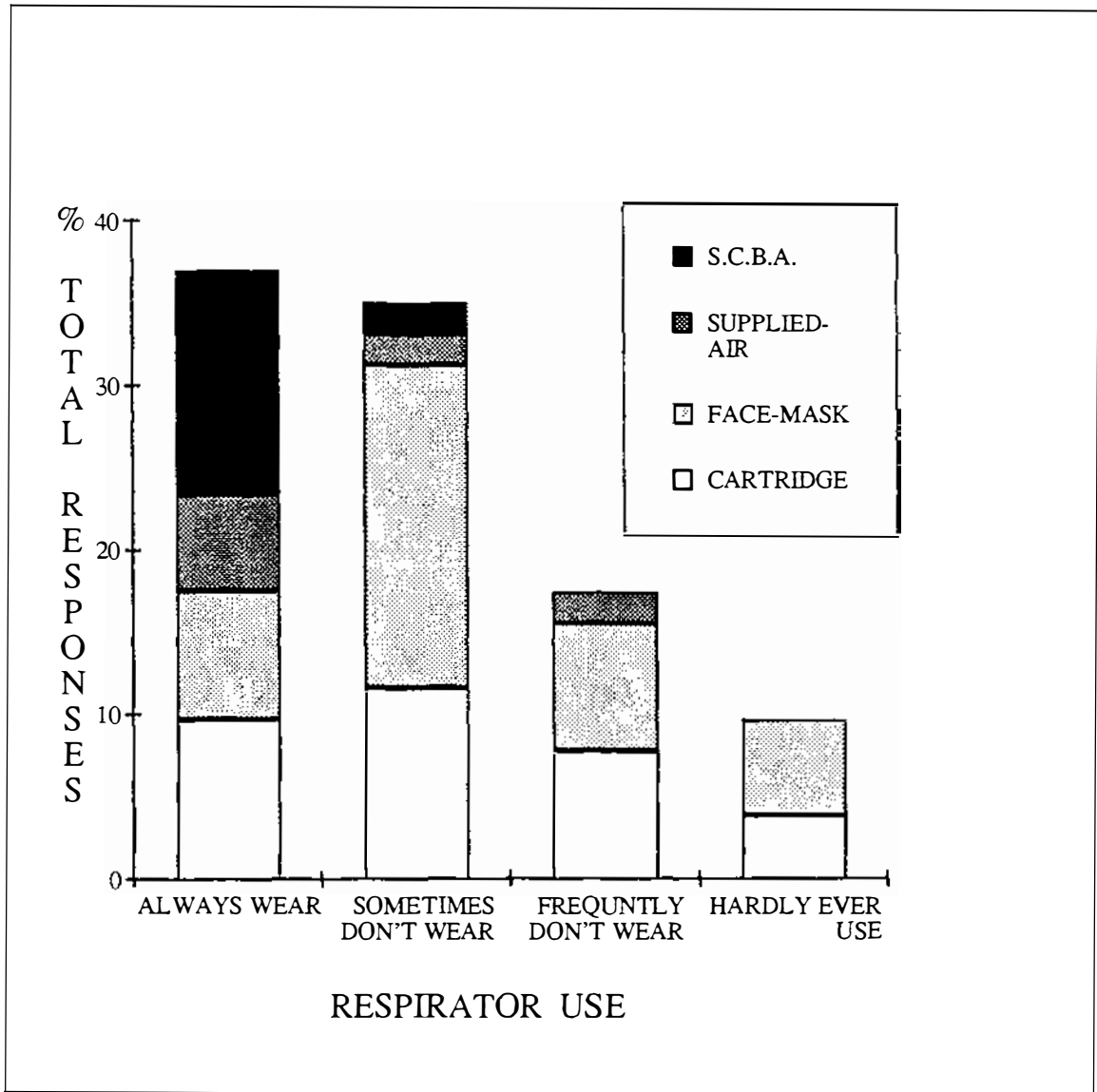
The most common form of respirator worn (73%) in the industries surveyed was the air-purifying types (ori-nasal half mask with cartridges/canisters or disposable dust-masks). Supplied-air respirators (15%) and self contained breathing apparatus (SCBA) (12%) accounted for the remainder.

The predominant types of work undertaken when wearing the air-purifying respirators involved agricultural chemical spraying (20%), chemical handling and mixing (19%), sanding and grinding (16%) and spraying industrial chemicals (16%). The use of the supplied-air respirators was most common when spraying and mixing chemicals (13%). Fire-fighting activities accounted for all the SCBA use (12%).

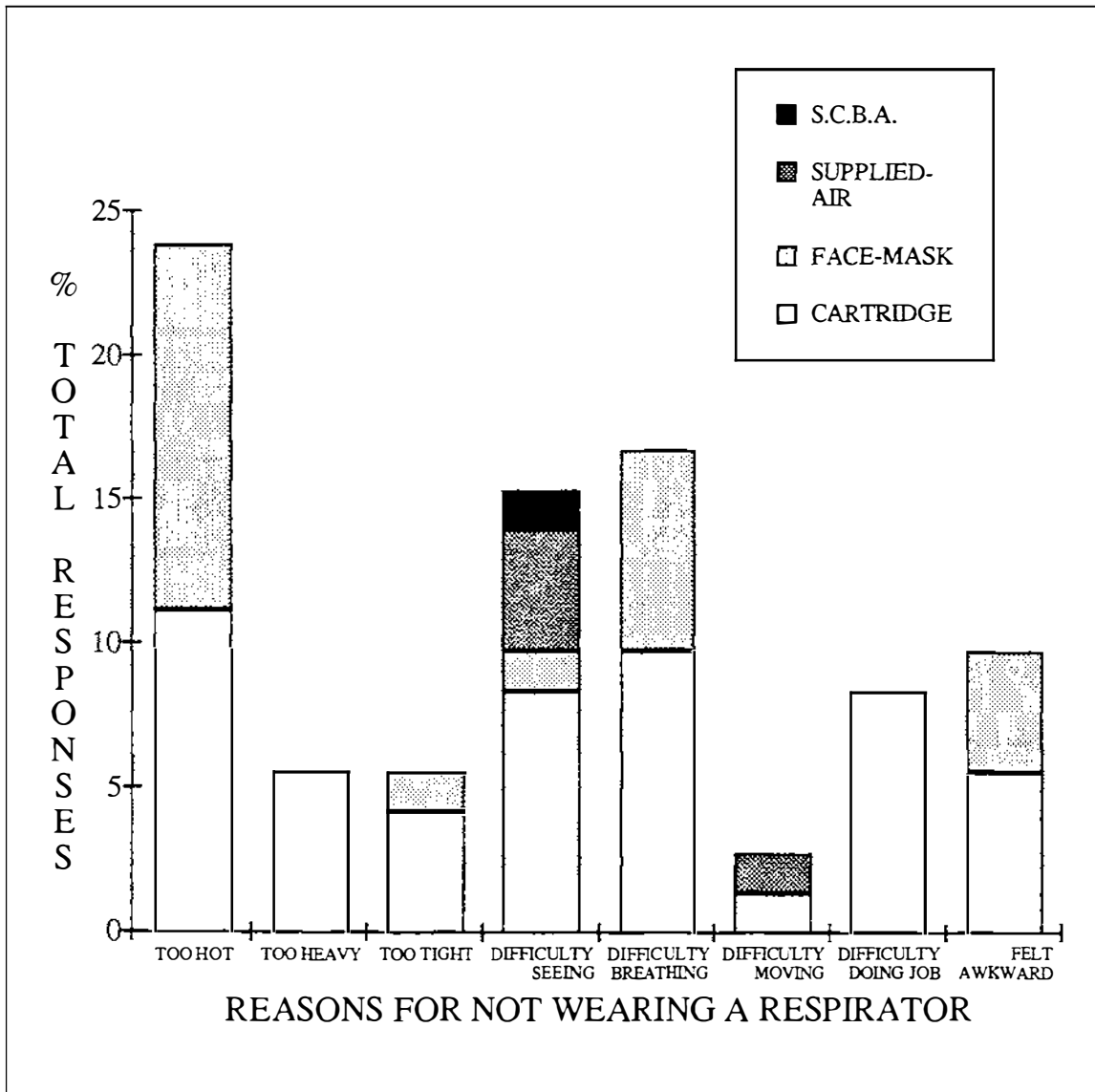
When asked how strenuous they felt their workloads were, 51% of respondents considered it moderate, 31% felt it strenuous and the remaining 18% felt it a physically light load. All SCBA users (fire-fighters) indicated their workloads were very hard. Of the respondents using air-purifying respirators (n=59), 32% found their workloads hard or very hard, 50% moderate and 18% light. Those using supplied air respirators all reported their workloads either moderate or light.



**Figure 2.1. The longest time the respirator was worn for each day or shift.** The Figure indicates that some air-purifying respirators were worn for long periods of the work shift. Nearly 20% of those using face-masks or cartridge filtration devices were required to wear them in excess of four hours in each shift. The use of SCBA by the fire Department personnel was confined to less than one hour.



**Figure 2.2. The frequency of use of respiratory protection.** In response to the question - "Do you ever take the respirator off, for some reason, before the work is finished?". The figure shows that most SCBA wearers always wear the equipment when required to so. This is to be expected due to the emergency situations encountered. However, a large proportion of those wearing air-filtration devices (50%) and a number wearing supplied-air devices (5%), occasionally or frequently do not use them. Including the 15 blank responses from non-users, 22% of those surveyed admit to never or hardly ever used the equipment.



**Figure 2.3. The most common reasons for not wearing the respirator.** The reasons included, that it felt too hot (24%), that the user experienced difficulty breathing (17%) and difficulty seeing adequately (15%). Other important reasons included feeling awkward or clumsy (10%) and difficulty doing the job (8%).

For those respondents who indicated they always wore a respirator, their reasons for this were their concern for their own health and avoidance of the inhalation of dusts and vapours. One respondent who removed a SCBA did so because of visual difficulties. i.e condensation within the enclosed full face-mask.

When the respondents were asked what type of advice was given to them on using, fitting and maintaining the respirator, nearly half (49%) of the users indicated they received no advice. The information that was given to the remainder concerned how to wear the equipment (35%), the reasons for its use (14%), maintenance information regarding replacing canisters/cartridges (30%) and disposal of spent devices (17%).

### 2.3.2 South Island Manufacturing Site

Of 150 respirator users approached, one hundred and five replied to the questionnaire (70.0% response rate). For the completed questionnaires (n=105, 102 males, 3 females) Table 2.3 shows the age characteristics of the respondents. In contrast to the Palmerston respondents, this sample group was proportionally older (70% between 30-50 years). The majority of the subjects were of European background (98%), the remaining 2% were of Maori or Pacific Island descent. Twenty four percent of the respondents indicated that they smoked.

**Table 2.3 Age Characteristics of Respondents (South Island Site).**

<u>Age Group (Yrs)</u>	<u>Number of respondents*</u>	<u>%*</u>
<20	0	0.0
20 - 29	16	15.2
30 - 39	40	38.1
40 - 49	33	31.4
50>	9	8.6
Total	98 + (7)	100.0

\* Expressed as % of all respondents.

# Seven respondents failed to detail age (N=105).



Virtually all respondents indicated they were exposed to dusts (97%). Most reported exposure to gases and fumes (87%), some reported exposure to vapours and mists (21%). They all considered they wore appropriate respiratory protection for these hazards. The most common reason given for wearing the respirator was as a precaution against a perceived hazard (63.4%). However, some reported they wore the device because of a management requirement to do so (26.8%).

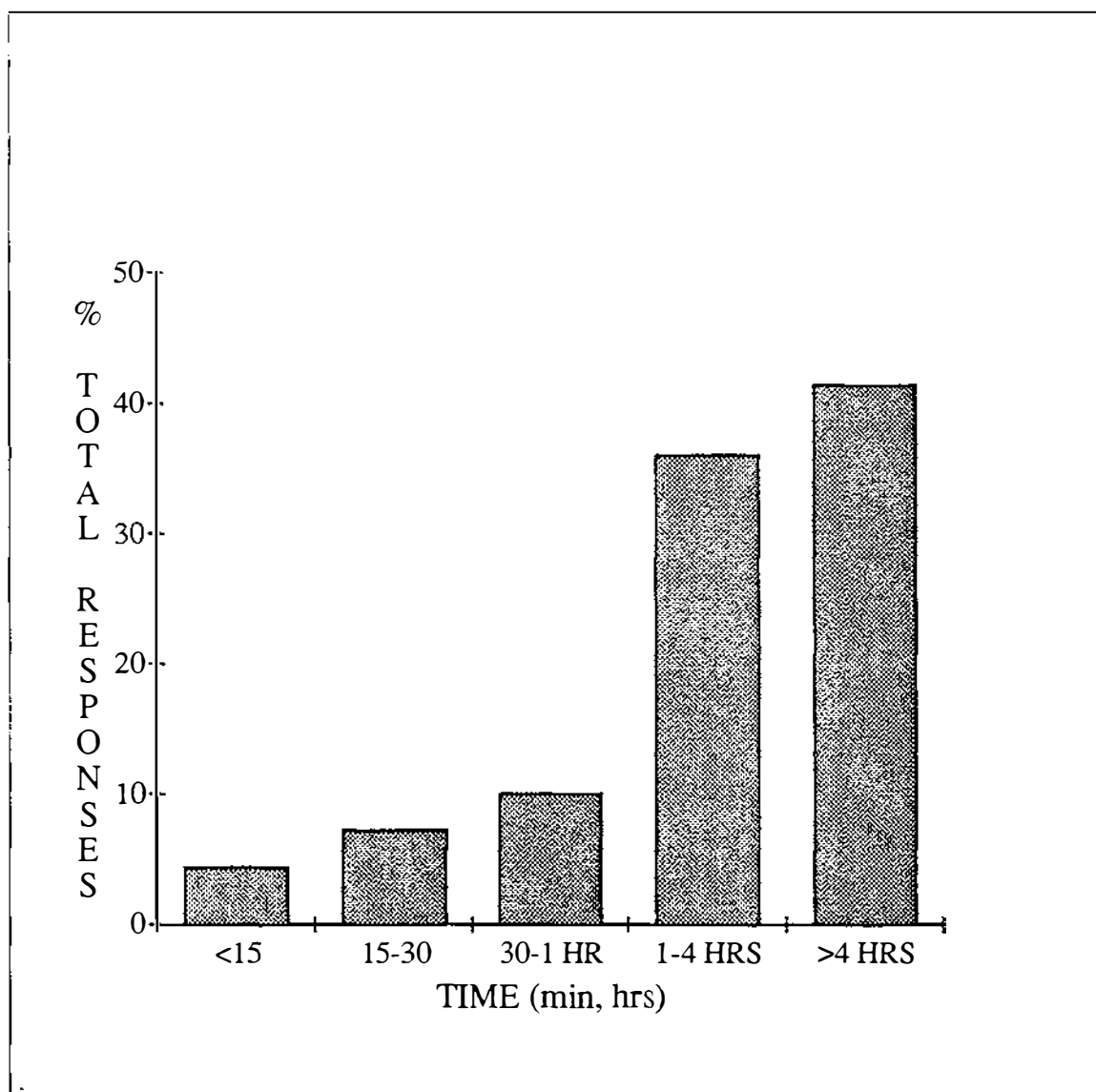
Knowledge of the health effects of exposure to the hazards was varied. A number of respondents indicated that excessive exposure to dust and fumes could lead to 'potroom asthma' (34%) or that exposure affected the respiratory system in some other way (39%). Some thought that the effects were generally harmful (25%). Nearly 17% of the respondents were unaware or unsure of the nature of the effects of exposure or the period of time over which exposure was hazardous. Seventy five percent of the subjects considered that exposure would be hazardous over a long period of time (months or years) rather than a short period (days or weeks).

The most common form of respirator worn (75%) on the site was the air-purifying types (ori-nasal half mask with cartridges/canisters or disposable dust-masks). Air - powered air purifying respirators were also in common use (25%).

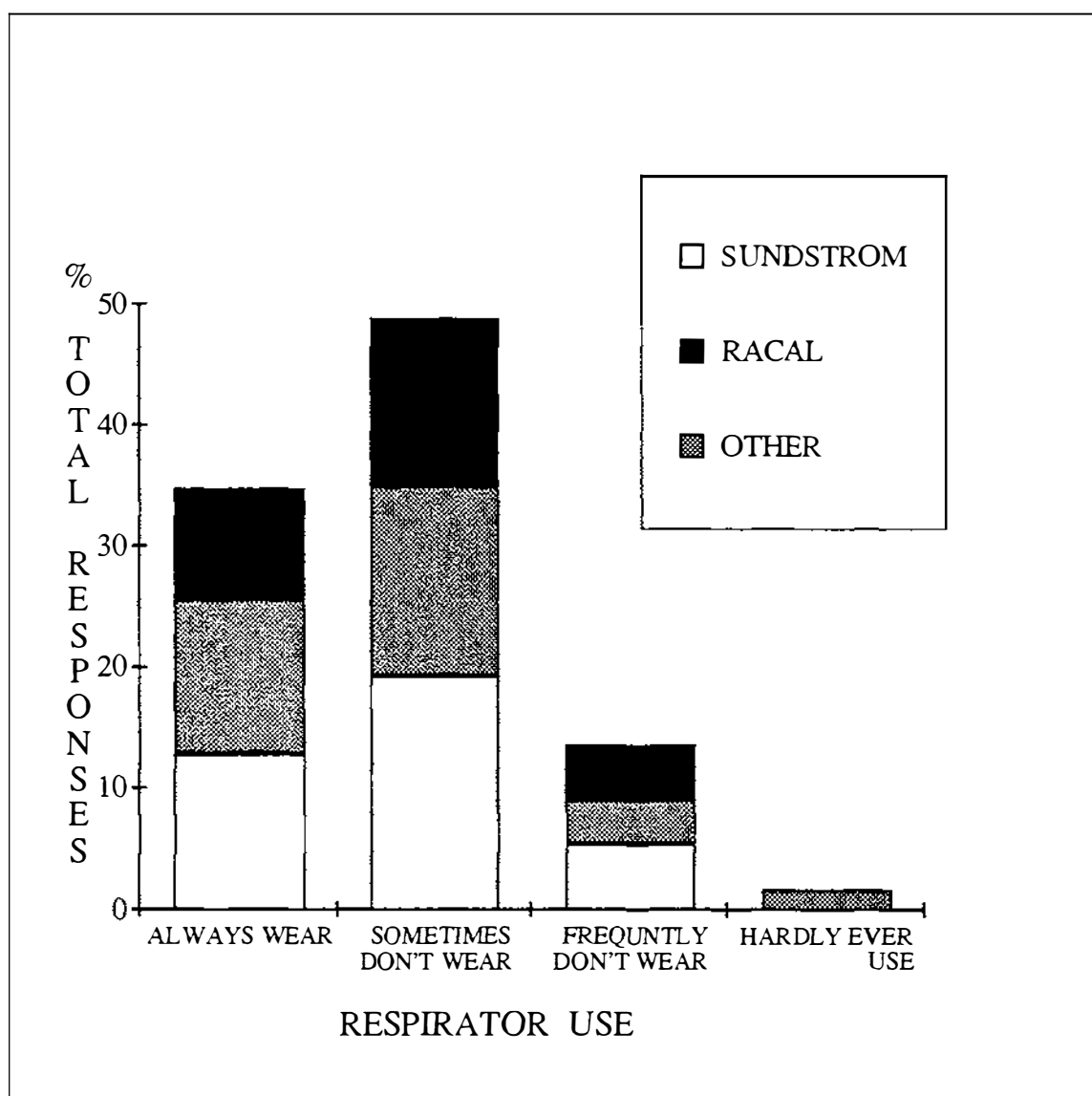
The predominant types of work undertaken when wearing the air-purifying respirators involved general potroom operations, inspections, cleaning, sweeping, casting metal, electrical and engineering maintenance, discharge bulk material from ships holds and supervision.

When asked how strenuous they felt their workloads were, 28% felt it strenuous or hard, 48% of respondents considered it moderate and the remaining 24% felt it a physically light load.

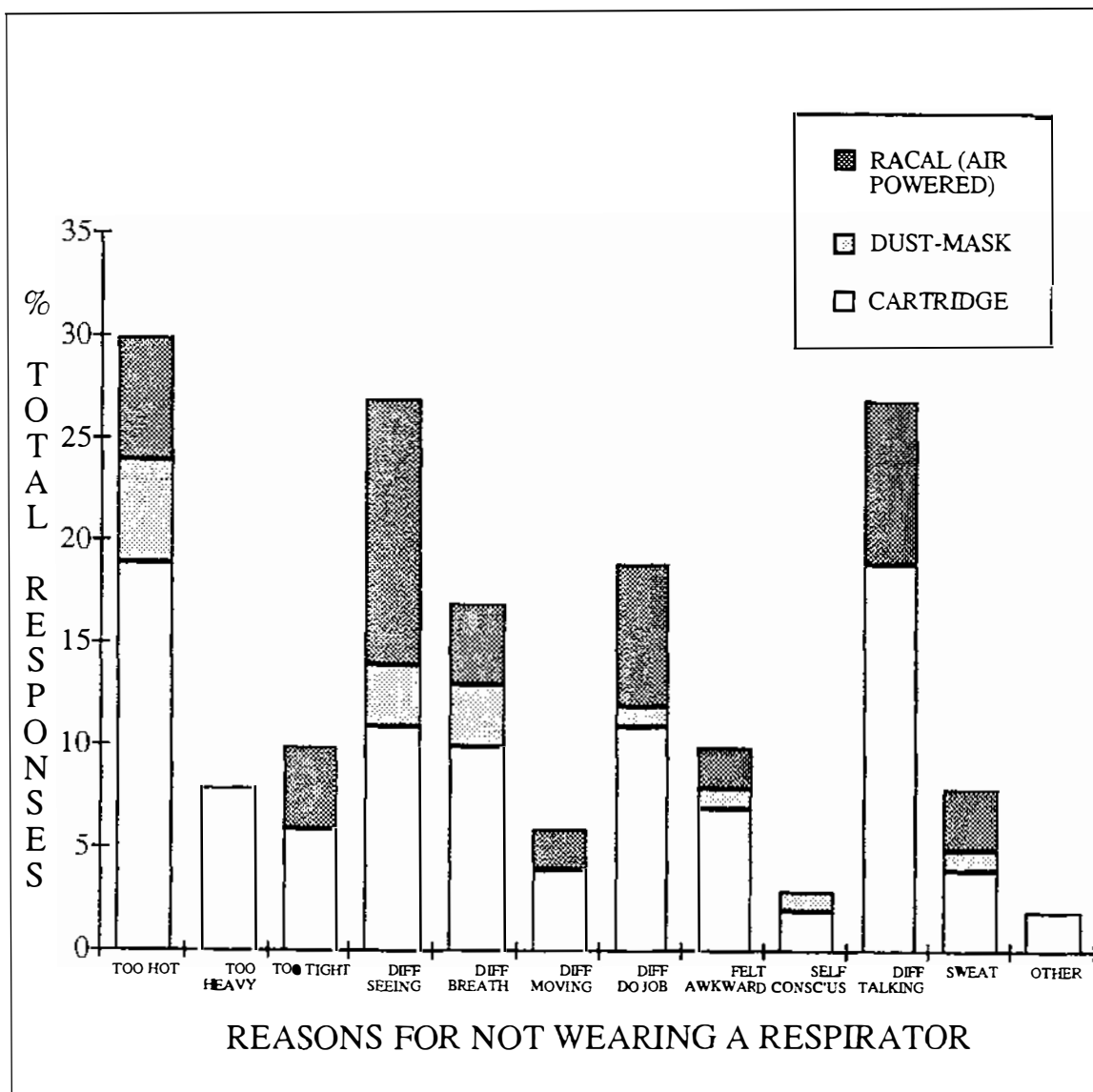
\* air is forced through the filter system



**Figure 2.4. The longest time the respirator was worn for each day or shift by South Island respondents.** The figure indicates that the use of air-filtration devices for over four hours was common for nearly half of those responding (42%). Very few respirator users wear them for short periods of time (up to 30 minutes).



**Figure 2.5. The frequency of respirator use** in the South Island survey. In response to the question - "Do you ever take the respirator off, for some reason, before the work is finished?". This indicates that over half of the respondents (63%) remove the respirator whilst undertaking work that may required its use. The 'other' category includes respirators primarily from 3M and Kemira and other types from alternative manufacturers. Respirators from 3M were both cartridge and dust-mask types.



**Figure 2.6. The most common reasons for not wearing the respirator from the South Island survey.** As the respirators were all of the air-purifying variety, the different makes are identified in the Figure. The Figure shows, problems of heat and condensation were a major reason for respirator non-use. Other important reasons for removal included being unable to communicate whilst wearing the mask and difficulty seeing. Difficulty breathing was not a significant reason for mask non-use in the individuals that responded. For those respondents who indicated they always wore a respirator, their reasons for this were their concern for their own health and avoidance of the inhalation of dust and fumes.

When the respondents were asked what type of advice was given to them on using, fitting and maintaining the respirator, twenty percent (20%) of the users indicated they received no advice, despite there being an active Occupational Health Unit at the site. The information that was given to the majority of users concerned how to wear and fit the equipment (55%), reasons for its use (44%) and maintenance information regarding replacing canisters/cartridges (50%).

A great variety of responses were given about difficulty in the use of respirators. Problems most frequently mentioned by respondents included; the difficulty of communication and vision, the discomfort caused with wearing the devices and the thermal stress.

Communication difficulties were a major concern to employees. The visual problems reported were created primarily by condensation fogging up safety glasses or face. Many problems of discomfort were identified by respirator users. They included sweating, chaffing of the face and skin rashes caused by straps. Also respondents felt the respirator was too heavy and there was excessive pressure on the face and nose. In addition, comments were reported that the respirator was too bulky and interfered with work and there was difficulty wearing the respirator in combination with other protective equipment (safety glasses and hard hat).

## **2.4 Discussion**

These studies are the first in New Zealand to survey the nature and extent of use of respiratory protective equipment in industry and provides evidence that non-use was quite common among those who place themselves at risk by not using the devices. These results confirm the evidence from earlier studies (Anon, 1970; Harris, 1974; National Coal Board, 1977) that the reasons for non-use are complex and involve problems with physical discomfort, difficulty in breathing, difficulty seeing and communicating.

A large proportion of respondents were exposed to dusts in the premises surveyed and

respiratory protection was worn as a precaution rather than as a requirement to do the work. This indicated that the decision to wear the equipment was largely one of choice by the wearer, rather than compulsion by management. It follows that use of a respirator may be linked to the users knowledge of the health effects of exposure. Respondents' knowledge of the health effects of exposure to air-borne contaminants were varied. However, over 10% of all individuals surveyed were unaware or unsure of the effects (10% Palmerston North, 17% South Island). A small proportion (5%) were able to give detailed descriptions of the symptoms of exposure, due to past experiences where they became aware of the health effects on themselves. It was of some concern that nearly 1 in 20 people of those surveyed had experienced clinical symptoms of exposure.

The results from the Palmerston North area indicated that air-purifying respirators were the most common form of respiratory protection worn in the premises surveyed. Of these the disposable dust mask type was worn by 30% and ori-nasal half masks with cartridges by 43%. This was appropriate for the type of work requiring this equipment which was prevalent in the area surveyed i.e. chemical handling and mixing, sanding and grinding and chemical spraying, including the use of agricultural and horticultural chemicals. This range of work activity would likely require protection from particulates, mists and vapours and it was found that some respiratory protection identified in the surveys was inappropriate for the hazard of concern. When these situations occurred, advice was given to the subject and employer on the correct protection required. Because of the nature of work undertaken at the South Island site i.e. large molten metal foundry situation with exposures to particulates, fumes and vapours, air-purifying respirators were most extensively used.

A surprising result was the respondents' perception of their workload when wearing a respirator. Table 2.4 shows the percentage of respondents that perceived their workloads to be hard, moderate or light in the two survey locations. Fire fighting has been shown to be a physically very demanding task by many authors (see:- Louhevaara, 1984 for review) and the fire fighters who responded indicated this. However, 23% of all other respondents, primarily wearing air-purifying respirators,

maintained that their workload was strenuous.

**Table 2.4 Percentages of subjects in the two survey areas that perceived their workloads to be physically hard, moderate or light.**

<u>Workload</u>	<u>P.N. Area*</u>	<u>South Island#</u>
Hard	31%	28%
Moderate	51%	48%
Light	18%	24%
Total	100%	100%

\* Palmerston North and Horowhenua area (n=81)

# South Island plant (n=105)

The length of time the respirator was estimated to be worn (Figs. 2.1 and 2.4) showed wide variation. It was interesting however, that air-purifying respirators were worn for considerable lengths of time i.e. between 1 and 4 hours or more. Little information was available to researchers on the length of time respirators are worn in industry (Harris, 1974; Aucoin, 1975; National Coal Board, 1976). These estimates are not precise and range from 10 minutes to over 3 hours. The expectation from health and safety professionals is that air-purifying respiratory protection is worn for relatively short periods of time (Epstein *et al*, 1982; Jette *et al*, 1990). The results of this survey provided evidence that this was not the case in the industries investigated in this survey. Supplied-air equipment was also used for extended periods and with similar circumstances to air-purifying respirators. Nearly 10% of those surveyed wearing supplied-air devices, wear them between 1 and 4 hours, with a small number (3%) wearing them in excess of 4 hours per day

The results of this survey are of some concern that 54% of those surveyed in

Palmerston North and 63% of those in the South Island site remove the equipment for a variety of reasons before the work that required the respirators' use for personal safety was completed (Figs. 2.2 and 2.5). Over 25% of those responding indicated a reluctance to wear the devices at all. This evidence supports an earlier American study (Aucoin, 1975) which revealed that respirators were worn for only 20-30% of the appropriate work time. It appears that many individuals voluntarily expose themselves to industrial hazards because of the discomfort or inconvenience of wearing respiratory protective devices.

Perceived difficulty in breathing was a prominent reason for non-use of air-purifying respirators in both surveys (19% P.N., 16% S.I.). Several groups have investigated the effects of air-flow resistance on the pattern of breathing by simulating the effects of respirators using external resistances and dead space (Shimozaki *et al*, 1988; Harber *et al*, 1984; Silverman *et al*, 1951) or by using modified respirators (Louhevaara, 1984; Laird *et al*, 1990). There is some evidence to indicate that increased expiratory resistance constitutes the most important perceived resistive load on the respiratory system (Louhevaara, 1984). However, whilst much is known about the effects of respirators on breathing - "such observations have not been correlated with surveys of respirator tolerance in the workplace" (Beckett and Billings, 1985). The air-purifying respirators used by respondents in this study have been evaluated to determine their flow-resistive characteristics (Laird *et al*, 1990). Inspiratory and expiratory resistances were found to be relatively low for most air-purifying respirators used in this survey (0.01-0.2 kPa/l/s) and comparable with values from other studies (see:- Louhevaara, 1984 for review). It should be of major concern that users are still reluctant to wear the devices even with these low resistances. In addition, it was interesting to note that difficulty breathing was ranked fifth in the responses given in the South Island survey. This was consistent with air-flow resistance determinations that indicated that the respirator most commonly used on the site (Sundstrom SR 90) exhibited comparatively low expiratory resistances and moderate inspiratory resistances (refer Chapter 3 section 3.2 for details).

The other major reason given by all respondents for non-use (Figs. 2.3 and 2.6), was



the problem of thermal discomfort. Neilsen *et al*, (1987a) evaluated the influence of air temperature and humidity inside respirators on mask acceptability, thermal sensation and perceived comfort of subjects working at different ambient temperatures. They commented that it was not known whether disuse of masks during industrial work was caused by a decrease in mask acceptability due to local warming or by a decrease in acceptability of "whole body" thermoregulatory conditions. The factors that cause a sensation of thermal discomfort are not well understood and that discomfort resulting from wearing the respirator has been attributed to a decrease in thermal exchange between the respirator wearer and the environment (Martin and Goldman, 1972; Martin and Callaway, 1974).

The temperature and humidity conditions inside respirators that cause a perception of thermal comfort are not precisely known. Furthermore, it is difficult to envisage how these might be modified to improve user acceptability. Studies of thermal discomfort (Neilsen *et al*, 1987; DuBois *et al*, 1990) have attempted to determine acceptable ranges of temperature and humidity under the respirator facepiece and have found that facial skin temperatures below and above 34°C mark a boundary between comfort and discomfort.

Little attention in the literature has been paid to the other reasons for non-use encountered in this survey. One of the most significant reasons given by respondents in the South Island survey, was the difficulty of communication. The device was often removed to talk to fellow workers. This increased the likelihood of exposure and possibly reduced the efficiency of the protection factor of the respirator. Difficulty seeing and moving were also important reasons for removal of the device by users of supplied-air and air-powered air purifying (Racal) respirators. Feeling awkward or self-conscious when wearing the equipment were also of concern to over 10% of the respondents who used air-purifying devices in both the South Island and Palmerston North surveys. The finding that half of the respondents in the Palmerston North study indicated that they received little or no advice on using, fitting or maintaining the equipment was also of considerable concern to the author.

Evidence from this survey not only provides information on patterns and frequency of respirator use, but also data from users of the equipment regarding their perceived reasons for non-use. The major factors identified in this study that are most able to be modified or corrected by manufacturers of respiratory protective equipment are those of:

- (i) reduction in breathing or air-flow resistance of the devices
- (ii) improving the ability of the user to communicate whilst wearing the device
- (iii) improve the visual efficiencies of the respirators
- iv) improve the adverse thermal conditions inside the respirator.

It was also apparent in the sites surveyed that employers had a genuine desire to improve workplace conditions in order to minimise the need for personal protection. The reasons for this will be expanded upon in the Discussion (Chapter 8). Respiratory protective devices will probably still need to be used by those working in industry for some time to come, therefore every effort should be made to improve the acceptability of the devices.

Having gained some appreciation of the problems encountered by respirator users, it is essential that we now examine the physical characteristics of the devices in some detail. The following series of laboratory studies will begin with these evaluations.

## CHAPTER 3

### 3.0 LABORATORY STUDIES ON THE PHYSICAL CHARACTERISTICS OF RESPIRATORY PROTECTIVE EQUIPMENT

#### 3.1 Introduction

This chapter describes a series of laboratory experiments undertaken to assess the physical characteristics of a range of dust-mask and cartridge type air-purifying respirators commonly used in workplaces in New Zealand. The features investigated were inspiratory and expiratory resistances, external dead space of the facepiece and weights of the devices. These features were selected for study as previous investigations (reviews by Raven *et al*, 1979; Louhevaara, 1984 and Louhevaara, 1986) and the present study (Chapter 2) have indicated that they contribute significantly as reasons for respirator non-use.

A respirator is a complex device and an understanding of the physical characteristics of the respirator and how these affect wearer work performance is, therefore, important. A fundamental starting point in the examination of the physiological costs of respiratory protection, is an evaluation of the physical properties of the equipment itself (Louhevaara *et al*, 1984). Once this information is obtained, it is appropriate then to consider the extent and nature of any additional stress the respirator imposes on the user.

Every respirator manufactured has its own unique characteristics and must comply with certain international standards e.g Australian Standard 1716-1991, for inspiratory and expiratory breathing resistances. The accepted standards for the physical characteristics of respirators cover a wide range (at 30 l/min the inhalation pressure drop must not exceed 1.2 mbar (120 Pa), while at 95 l/min the drop must not exceed 3.7 mbar (370 Pa); exhalation resistance at 85 l/min should not exceed 1.2 mbar (120 Pa)). How individual makes and models that are available in New Zealand rate within this range is unknown.

**Table 3.1 Exhalation resistance values at varying flow rates obtained by Burgess and Anderson (1967).** The resistances have been recalculated as the original values were in inches of water.

Type of Valve	Resistance to Flow at 40 l/min (Pa)	Resistance to Flow at 85 l/min (Pa)	Resistance to Flow at 200 l/min (Pa)
Mushroom	69	151	416
Annular	62	79	305
Flap	119	208	644
Poppet	34	81	220

**Table 3.2 Air-flow resistances for an air-purifying respirator (Kemira Silner 12).** Undertaken by Louhevaara *et al*, (1984) for continuous inspiratory and expiratory flow rates.

Direction of Flow	Resistance to Flow at 40l/min (Pa)	Resistance to Flow at 85 l/min (Pa)	Resistance to Flow at 200 l/min (Pa)
Expiratory	60	140	350
Inspiratory	140	300	800

Difficulty in breathing has been suggested to be a major factor in the failure by individuals to wear or use respirators, particularly at high workloads (Craig *et al*, 1970; Hermansen *et al*, 1972; Raven *et al*, 1977; Morgan, 1983; Louhevaara *et al*, 1984). Whilst some studies have shown little evidence for this at submaximal workloads (Hermansen *et al*, 1972; Steinhaus *et al*, 1984), other studies indicate that, even at low work levels, increased expiratory resistance constitutes the most important resistive load on the respiratory system (Demedts and Anthonisen, 1973; Gee *et al*, 1968). In "cartridge type" air purifying respirators the major expiratory resistance is caused by simple one-way valve systems (Burgess and Anderson, 1967; Lundin and Colton, 1988). Early experiences with problems associated with expiratory resistance of valves was reported in the 1952 Mount Everest expedition. Climbers reported major discomfort created by the expiratory valve of the oxygen respirator 'flapping' (Cotes, 1962). Since that time, research on the performance of inspiratory and expiratory valves has not been particularly extensive.

Burgess and Anderson (1967), tested the operating pressures, resistance to flow and dynamic leakage of expiratory valves used in air-purifying respirators. These authors found significant differences in performance between the four major valve types (mushroom, annular, flap and poppet types). Of these the mushroom and annular type valves were shown to have moderate airflow resistances, with the poppet type valve having the lowest resistance tested. The flap type valves were shown to have the highest exhalation resistances. Table 3.1 summarises the results obtained by Burgess and Anderson (1967). Later studies (Corn, 1980; Campbell *et al*, 1990) suggested several areas of respirator design that required further attention. These included improvements to respirator materials and components (particularly valves) and saturation indicators for cartridges.

Louhevaara *et al*, 1984 investigated the cardiorespiratory effects of wearing air-purifying, supplied-air and SCBA. The relative inspiratory and expiratory resistances of the devices were also documented. Both inspiratory and expiratory resistances of air-purifying devices showed a non-linear relationship to flow rates. The range of resistances for an air-purifying respirator are shown in Table 3.2.

The values obtained by Louhevaara *et al*, (1984) for expiratory resistances can be compared with the exhalation resistances measured by Burgess and Anderson (1967) (Table 3.1). The expiratory valve system in the respirator (Kemira Silner 12) used by Louhevaara *et al* (1984) was a simple 'flap' valve. Tables 3.1 and 3.2 show that inspiratory resistances are double the expiratory resistance values. The higher resistance is due to the inspired air being pulled through the filtration system of the air-purifying respirator (Ballantyne and Schwabe, 1981; Lundin and Colton, 1988).

Air-purifying respirators have been shown to be the devices most frequently used in New Zealand manufacturing and agricultural industries (Chapter 2). This is also the case for other industrialised countries e.g Europe and the United States (Ballantyne and Schwabe, 1981; Louhevaara, 1984; Jones, 1991).

Added inspiratory breathing resistance during submaximal and, particularly, maximal exercise hinders ventilation and results in hypoventilation and the retention of carbon dioxide (refer reviews by Raven *et al*, 1979; Louhevaara, 1984). Alveolar-arterial oxygen gradients are found to be unchanged (Gee *et al*, 1968).

The importance of external dead space and its effects on minute ventilation and tidal volume have been studied by a number of authors (James *et al*, 1971; Bartlett *et al*, 1972; Kelman and Watson, 1973; Sackner *et al*, 1980; Harber *et al*, 1982). Most studies indicate a near linear increase in minute ventilation and tidal volume as the size of the external dead space increased. The effects of the extra weight of the respirators has been shown in some studies to affect ventilation, oxygen consumption and heart rate at submaximal work levels (Louhevaara *et al*, 1984; Louhevaara, 1984).

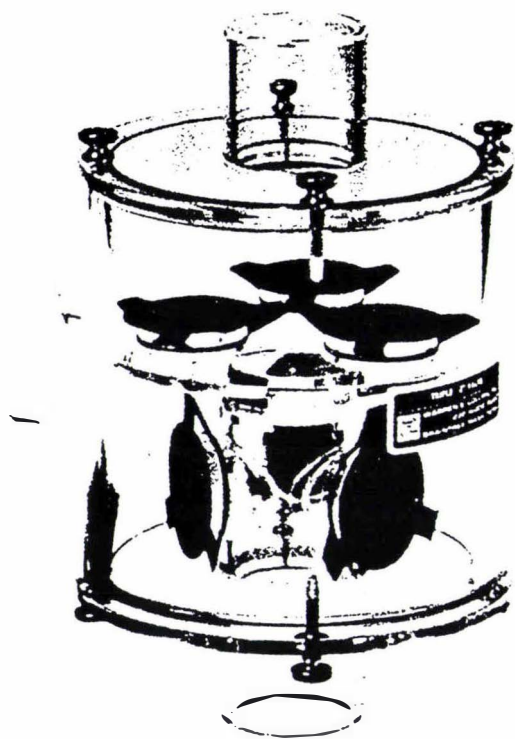
While studies to date have assessed the resistance of respirators at constant flow rates (refer reviews by Raven *et al*, 1979; Louhevaara, 1984; Louhevaara *et al*, 1984; Louhevaara *et al*, 1986), few studies have measured resistances using reciprocating flows (Cooper, 1960; DuBois *et al*, 1990). One study (DuBois *et al*, 1990) did undertake an evaluation of a respirator using tidal breathing, but the study assessed the

thermal discomfort and not the airflow resistances of the respirator. It has been suggested (Cooper, 1960) that the use of reciprocating flows would seem a more appropriate method for resistance determinations as it takes into account:

- (i) The dynamic nature of the breathing cycle, including the changes from negative to positive pressure within the facemask.
- (ii) The additional resistances imposed by the opening and closing of the inspiratory and expiratory valves and,
- (iii) The additional respiratory burden required to move the residual 'dead space' air in the facemask.

The reciprocating flows originally chosen by Cooper (1960) ranged from 5 -100 l/min. The author stated that these were the approximate minute volume values likely to be experienced by respirator users in practice. Louhevaara *et al*, (1984), evaluated pulmonary ventilation of subjects with and without respirators at work levels between 20-60% maximal oxygen uptake and corresponding minute ventilation ranged between 23-60 l/min. Corresponding values for reciprocating ventilation were used in the present study.

The present study was undertaken to determine the static and dynamic flow-resistance characteristics, the dead space and the overall weight of a selection of air-filtering respirators commonly used in industry in New Zealand. The flow rates selected for use in this study were determined firstly, by their previous use in standards testing procedures and requirements for respirator design and manufacture (Australian Standard No.1716-1991; Respiratory Protection Devices) and secondly for comparison with values obtained in earlier studies (Burgess and Anderson, 1967; Louhevaara *et al*, 1984; Jones, 1991). The standard requires (i) for inhalation resistance - continuous airflows of 30 and 95 l/min were required and (ii) for exhalation resistance - continuous flows of 85, 100, 200 and 300 l/min. A single airflow of 85 l/min for exhalation resistance is prescribed in The Standard, which is said to correspond to peak air speed through the mask for an individual walking at moderate pace (Australian Standard, 1991). The values of 100, 200 and 300 l/min were included for comparison with other studies (Raven *et al*, 1979; Louhevaara *et al*, 1984;



**Plate 3.1 The Triple "J" High Velocity Breathing Valve used as a comparison for inspiratory and expiratory resistance measurements.**



Louhevaara, 1984), that used these extreme values to test devices beyond their normal operational limits.

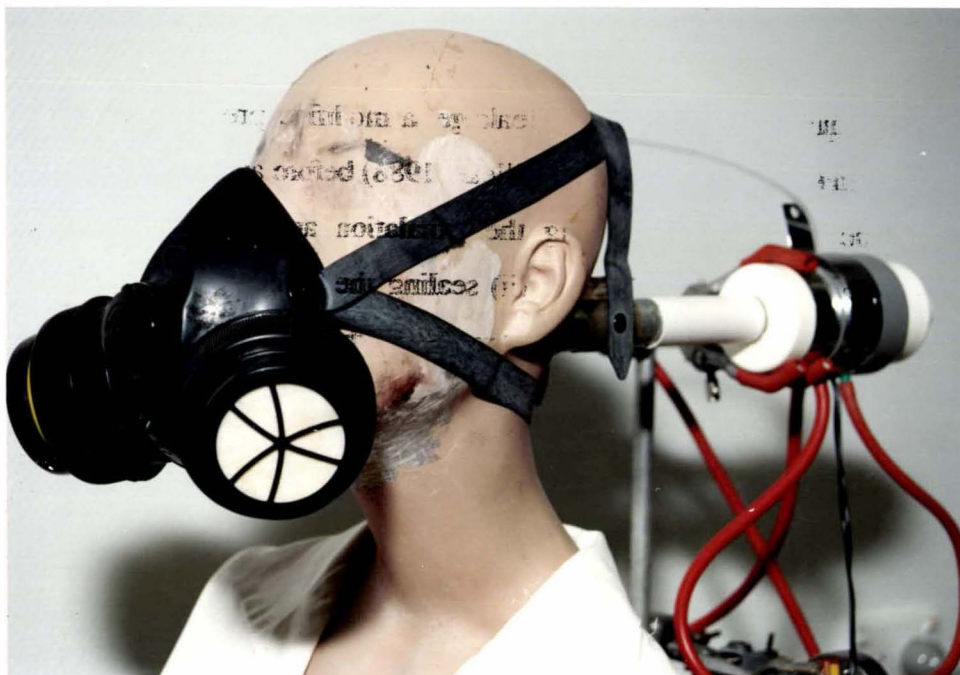
## 3.2 Materials, Method and Equipment

### 3.2.1 Respiratory Protective Equipment

Eight air-purifying respirators were studied (Sundstrom SR 90, Kemira Silner 12, Protector twin and single cartridge types, Norton 7700, Moldex #3400 dust-mask and 3M dust masks #9900, #9920). All devices were new and had clean filters. Five were ori-nasal half mask respirators with either single or double cartridges and single or twin exhalation valves; three were of the dust mask variety, two with one exhalation valve only and one with no valve system. All cartridges used were described by the manufacturers as providing protection against organic vapours. As a control device, a high velocity breathing valve (Warren E. Collins Inc. P-338 Triple "J") was also included. The valve (Plate 3.1) is cylindrical which permits the use of three "J" valves in the inspiratory and expiratory circuits. Inspiratory and expiratory resistance measurements are found to be extremely low at flow rates below 200 l/min (refer pressure-flow chart for P-338 Triple "J" High Velocity Valve, Appendix 2). The valve is designed for applications where highest flow rates in normal subjects are encountered (e.g. severe exercise regimens, maximal stress tests).

### 3.2.3 Experimental Technique

Each respirator was mounted on a dummy head which was modified to include a pressure sensing probe located below the nares and connected to a Validyne pressure transducer (Type SS45-16). The pressure transducer had a fast response time (less than 10 msec) and was able to operate within a range of operating pressures (0 to 2.45 kPa). A 20 mm internal diameter aluminium tube was moulded into the mouth of the dummy to act as the airway. It provided laminar (Reynolds number,  $Re < 2100$ ) air flow conditions with continuous flows for flow rates up to 100 l/min through the head. An air-tight seal around the respirator facemask was obtained by applying silicon



**Plate 3.2 Dummy head with respirator in place.** The pressure sensor is located under mask. The pneumotachograph is positioned at the rear of the 20mm mouth tube.

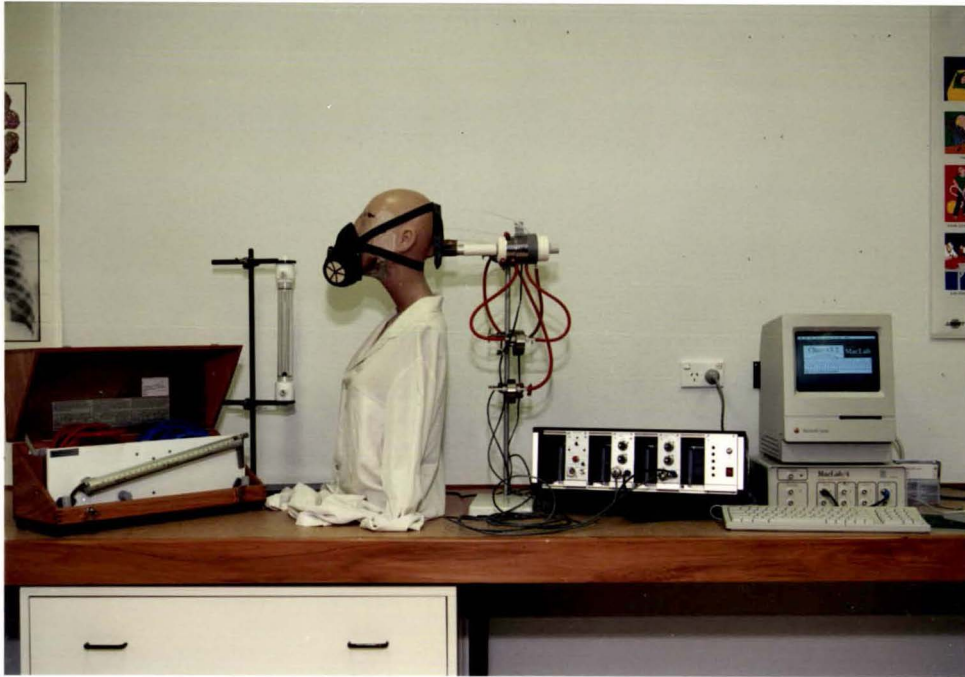
weather sealant/adhesive to the dummy head and fitting the respirator securely to it (Plate 3.2). Flow rates were measured using a Fliesch pneumotacograph (head size 25mm) and Validyne pressure transducer (Type SS45-16). The pneumotacograph was calibrated against a Tokyo Keno flowmeter (readability  $\pm 2.0\%$ ) and positioned behind the dummy head by a connection to the airway tube.

To ensure adequate seal and test for leakage, a modified pressure decay evaluation was undertaken (after Carpenter and Willeke, 1988) before and after each assessment. The technique involved; (i) sealing the exhalation and inhalation valves of the respirator with airtight plastic taping (ii) sealing the 20mm aluminium airway tube aperture with airtight plastic taping (iii) mounting the respirator on the dummy head, applying silicone sealant to the face of the dummy head and (iv) artificially pressurising the facemask using a 5ml syringe, which produced a small positive pressure inside the facemask.

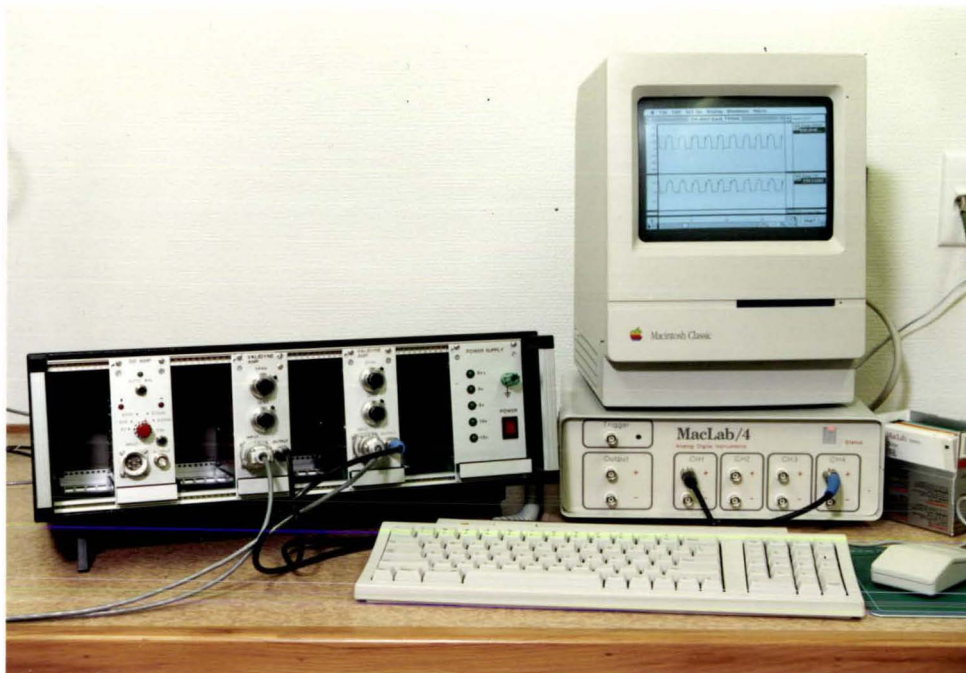
The pressure was then monitored for 30 seconds to identify any pressure loss due to leakage of the seal or valves systems. Leakage was identified as a pressure decay over this period of time (30 sec) and as a result the need for further sealing established. Experiments on flow resistive characteristics were not undertaken until a satisfactory pressure decay curve was obtained. Pressure decay values in excess of 20 Pa/min were considered to be unacceptable. A pressure decay evaluation was also performed after the reciprocating and continuous flow measurements were taken to ensure that no leakage had occurred during the assessment period.

### 3.2.3 Experimental Measurement

When acceptable pressure decay values were obtained from the leakage determination technique, the valve and airway tube seals were removed and the respirator arranged in a normal configuration.i.e. the appropriate cartridges (air filters) were fitted to the inhalation valve system.



**Plate 3.3** Experimental equipment used for the determination of air-flow resistances of respirators. The pneumotacograph is connected to the dummy head, the pressures and flows are measured by a manometer and flow meter (left) and the data recorded and analysed by Validyne amplifiers and MacLab system (right).



**Plate 3.4** J-Rak system with Validyne amps, four channel MacLab digital integrator and MacLab Chart application software depicted on Macintosh screen. Reciprocating flows depicted on screen (volume top section, pressure lower section).

### 3.2.3.1 Reciprocating Airflow Measurements

Reciprocating airflow was induced using a standard animal ventilator (G.F.Palmer) with a maximum tidal volume of 800cc. Pressures were calibrated against a 10cm water manometer for reciprocating flows and against a 30cm manometer (Airflow Instruments, Type 5) for continuous flows (reading accuracy  $\pm 1.0\%$ ). Data was collected and analysed through a Maclab (Maclab/4) four channel analogue to digital converter (Analog Digital Instruments Pty Ltd, NSW, Australia, 1989) (sampling - 5 kHz @  $\pm 2\text{mV}$  frequency response) and Maclab Chart/4 (Version 3.1, Analog Digital Instruments Pty Ltd, NSW, Australia, 1990) applications software (Plates 3.3 and 3.4).

Resistance determinations using reciprocating flows were made after the standard method described by Cooper (1960) i.e. resistance is directly proportional to the rate of air flow and is the product of pressure over volumetric rate of flow. This pressure-flow relationship can be diagrammatically illustrated on an oscilloscope screen or its computer generated equivalent. The slope of the loop generated is a measure of respirator resistance. The resistances of the respirators and the breathing valve were measured at reciprocating flow rates of 10, 20, 30, 40, 50, 60 and 70 l/min, using a standard piston ventilator capable of peak flow rates of up to 80 litres per minute.

### 3.2.3.2 Continuous Airflow Measurements

Continuous flow measurements were undertaken with the same equipment used in the reciprocating flow determinations with the following modifications. Flow was measured with a 40 mm pneumotachograph (A.Fliesh, Terrain 830.15, AS1477/2 Cl.18, calibration No.1737,  $1\text{mm H}_2\text{O} = 1.529\text{ l/sec}$ ;  $5\text{mm H}_2\text{O} = 7.648\text{ l/sec}$ ;  $10\text{mm H}_2\text{O} = 14.73\text{ l/sec}$ ), calibrated against a Gilmont flow meter. The animal ventilator which produced reciprocating flows, was replaced by a commercial vacuum cleaner motor modified to give continuous positive and negative air flows. The type used (Husqvarna Turbo 1100 Watt) had a variable flow rate mechanism to enable the flow rates to be varied. These rates (simulating inspiratory and expiratory peak flows) ranged from 85 to 300 l/min (positive and negative pressures). Laminar flows were

possible to achieve with flows of up to 100 l/min ( $Re < 2100$ ). Flows higher than these resulted in turbulent flows ( $Re > 2100$ ). Studies of the effects of respirators on minute ventilation (Louhevaara *et al*, 1984), showed that maximal values for minute ventilation in the 12 subjects ranged from 108-141 l/min (mean  $126.5 \pm 13.7$ ; mean ages  $26 \pm 4$  yrs).

#### 3.2.4 Facemask Dead Space Volume Measurement

The volume inside the respirator facepiece (external dead-space) was measured by volumetric analysis i.e. by filling the facepiece with 1mm small beads. The dummy head was then firmly fitted to the filled mask to ensure the facial features (nose, mouth, cheek bones and chin) were incorporated in the volumetric determinations. The beads were then weighed to estimate volume. The bead weights were calibrated against standard water volumes equivalent to 10, 25, 50, 100, 200 and 500 ml. Duplicate measurements were undertaken to determine errors of reproducibility ( $\pm 1.6\%$ ).

#### 3.2.5 Respirator Weights

The weights of the respirators (empty, with straps and cartridges) was determined using a standard balance (Mettler BB 600). The respirator was placed centrally on the weighing tray. Duplicate measurements were taken to obtain measurement/reproducibility indices. (Readability of the balance was to 0.01 g, reproducibility of measurements was  $\pm 0.03$  g).

#### 3.2.6 Statistical Analysis

Least squares regression analyses were undertaken for reciprocating and continuous flows on each pressure-volume evaluation (Microsoft Chart, Version 4, 1988). Regression equations were derived for (i) each set of pressure-volume loops using reciprocating flows and for (ii) each continuous flow evaluation, using the statistical analysis programme Minitab (Version 6.1, 1989).

### 3.3 Results

#### 3.3.1 Reciprocating Flow Measurements

The following Table 3.3 summarises the reciprocating flow measurements for each respirator (Appendix 2). Using least squares regression analysis for each peak flow, the regression equations are listed together with estimated resistance<sup>\*</sup> value for each respirator calculated at a flow of 85 l/min. The standard error of the prediction is also given.

**Table 3.3 Regression equations for the for the pressure-volume relationships of the respiratory protective devices assessed using reciprocating flows.** Units are (y) pressure (kPa) and (x) flow (l/min).

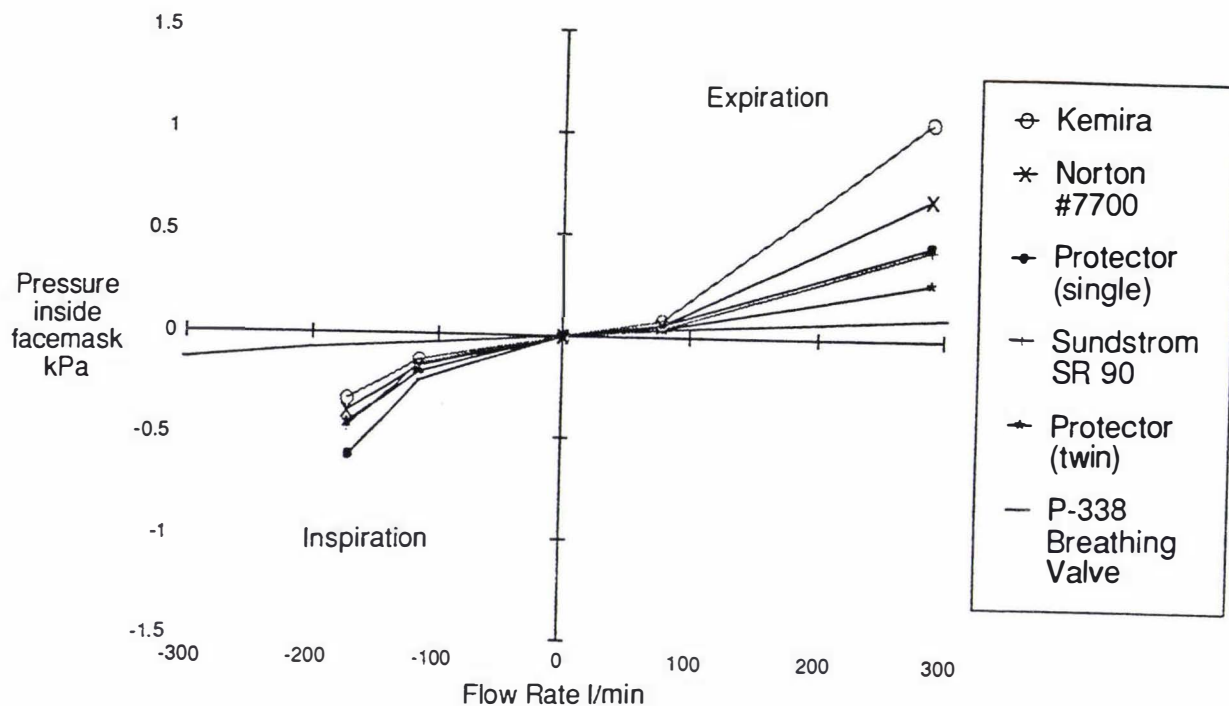
Respirator Type	Regression Equation <sup>+</sup>	S.E
3M #9900	$y = -0.44 + 1.03x$	2.62
3M #9920	$y = -0.44 + 1.57x$	5.55
Moldex #3400	$y = -1.41 + 1.48x$	3.29
Sundstrom SR90	$y = 2.56 + 0.78x$	3.1
Norton 7700	$y = -1.94 + 1.21x$	2.81
Protector (Twin)	$y = -1.67 + 1.36x$	3.71
Protector (Single)	$y = -1.72 + 1.41x$	3.38
Kemira Silner 12	$y = 3.00 + 3.08x$	4.9

+ Equation derived using least squares regression (Microsoft Chart)

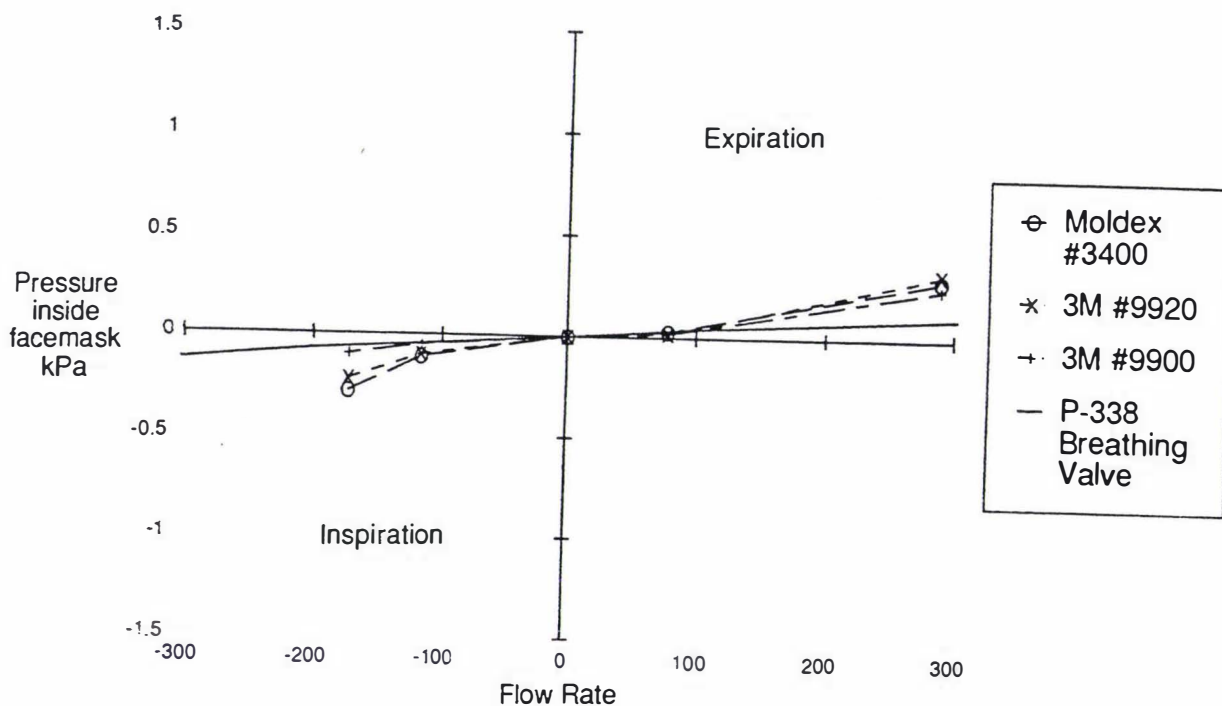
The Table illustrates that resistance is determined by the relationship between pressure and volume per unit time. The Sundstrom SR 90 respirator exhibited the least resistance and the Kemira model, the most resistance.

\* (refer to Table 3.4)





**Fig. 3.1** Continuous flow resistance measurements for cartridge type respirators. Inspiratory resistances are found to be higher than expiratory resistances.



**Fig. 3.2** Continuous flow resistance measurements for dust mask type respirators. Inspiratory resistance are greater than expiratory resistances but not to the same extent as with cartridge type respirators.



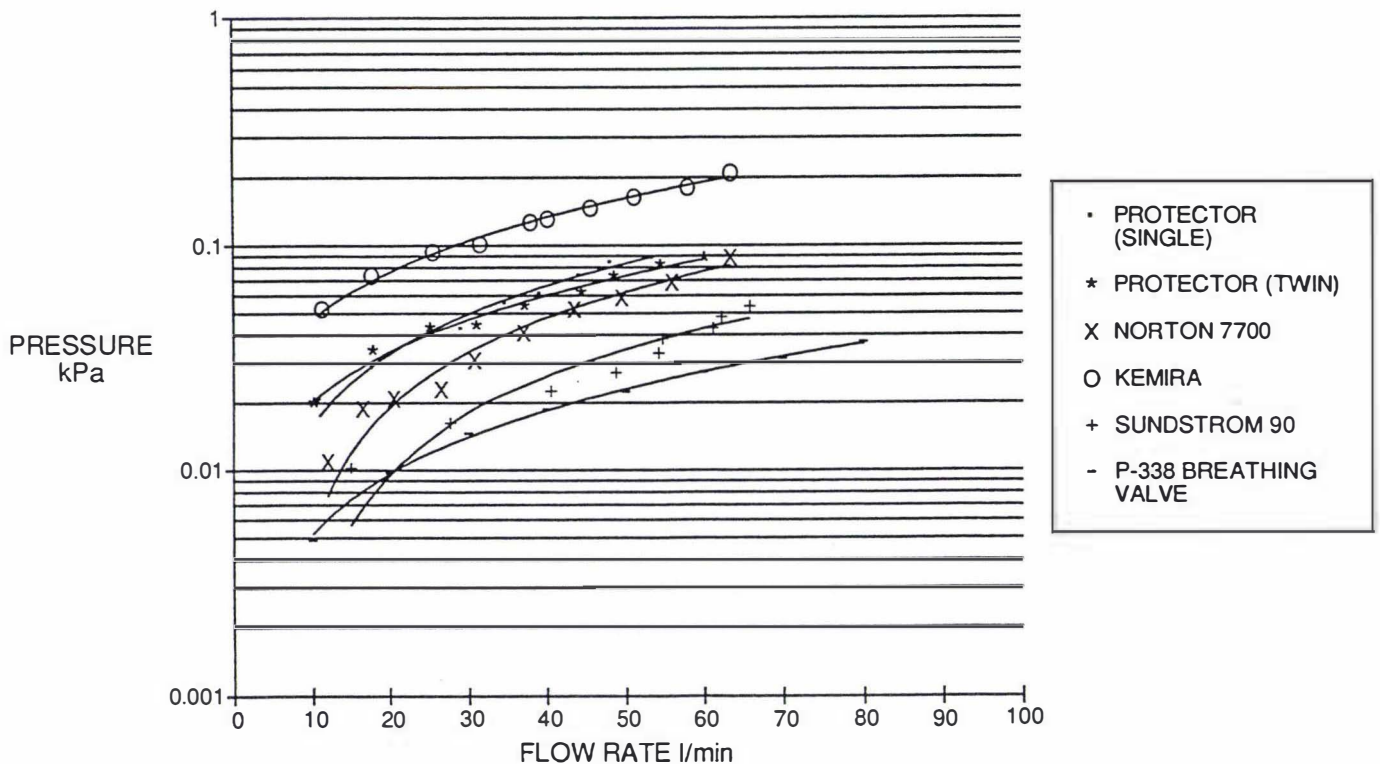
The Figures in Appendix 2 (A2.1 - A2.8) show the pressure-volume curves for the eight respirators using reciprocating flows, with flows ranging from 5 - 70 l/min. The relationships obtained for the dust-mask type of respirators (3M #9900, #9920, Moldex #3400), Figs. A2.1 - A2.3 showed comparably low inspiratory and expiratory resistances at low volume flow rates (10 - 30 l/min). At flow rates up to 70 l/min pressures inside the mask ranged from 0.01 - 0.1 kPa.

Of the cartridge type respirators the Sundstrom device exhibited the least resistance of all those evaluated. The respirator showed comparable pressure values to the dust-mask type respirators at low volume flow rates less than 30 l/min (0.015 - 0.030 kPa). At higher flows, pressure ranges from 0.025 - 0.06 kPa were recorded (Fig. A2.4). The Kemira device showed the greatest range of pressure values for a wide range of flow rates. i.e 0.005 - 0.05 kPa at 10 l/min, 0.004 - 0.08 kPa at 20 l/min, 0.08 - 0.105 kPa at 30 l/min and up to 0.20 kPa for flows > 40 l/min. (Fig. A2.8). The remaining respirators (Norton and Protector) Figs. A2.5 - A2.7, showed intermediate resistance ranges between the two described i.e. Sundstrom and Kemira. Values of 0.030 - 0.050 kPa at 30 l/min and up to 0.080 kPa for flows of greater than 40 l/min. A significant feature of these pressure-volume loops is the evidence of valve effects at the peak of the loop. The effect due to the opening and closing of the expiratory and inspiratory valves, is seen as a vertical or horizontal displacement of pressure. The dust mask 3M #9900, that does not have a valve system, shows no comparable displacement.

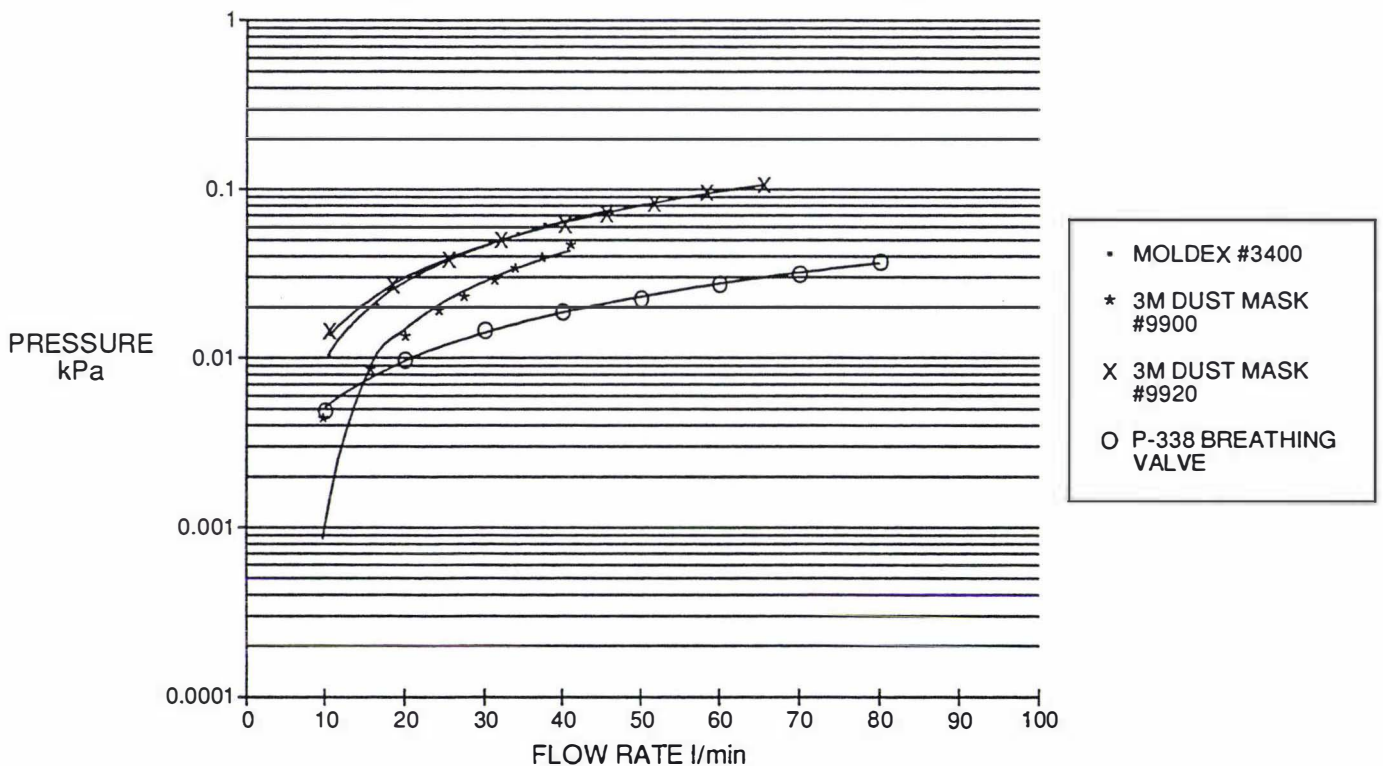
### 3.3.2 Continuous Flow Measurements

Results from the continuous inspiratory and expiratory flows are shown in Figs. 3.1 and 3.2. The figures show a wide range of pressures for cartridge respirators at high expiratory flow rates (270 to 300 l/min) of between 0.30 to 0.80 kPa. Pressures from inspiratory flows were higher than for expiratory flows (0.30 to 0.70 kPa at 180 l/min). This confirms that air being drawn through the cartridge significantly increases resistance.

Expiratory resistances for the dust mask variety of respirators were relatively low



**Figure 3.3** Pressure-volume curves for cartridge type respirators and the breathing valve. Pressures are shown for the respirators and the P-338 breathing valve at reciprocating flow rates of between 10 and 60 l/min.



**Fig 3.4.** Pressure-volume curves for dust-mask type respirators and the breathing valve. Pressures are shown for the masks and the P-338 breathing valve at flow rates between 5 and 70 l/min.

(pressures of 0.1 to 0.2 kPa at 180 l/min) which corresponded to twice the resistance measured for the breathing valve. Resistances for the cartridge respirators produces pressures that ranged from 0.2 to 0.5 kPa at 180 l/min and nearly five times higher than the value for the breathing valve. Inspiratory resistances for the dust masks were up to three times greater than the breathing valve producing pressures of 0.1 to 0.3 kPa at 180 l/min. Values for the cartridge devices were three to six times greater than corresponding values for the breathing valve (pressures of 0.3 to 0.6 kPa at 180 l/min). At higher flow rates (>200 l/min), a significant difference ( $P<0.001$ ) in resistances were seen between respirators with a twin exhalation valve system (Sundstrom and both Protector respirators) and those with a single valve (Kemira and Norton). This difference was not significant at lower flow rates ( $P>0.1$ ) (Table 3.4).

At high (>200l/min) flow rates the resistances of the dust mask type respirators are similar (0.05-0.06 kPa/l/s). At these flows the exhalation valve does not appear to offer any noticeable reduction in resistance. The result of the present study indicate that at lower flow rates (up to 85 l/min) and using continuous airflows, the inspiratory and expiratory resistances of the respirators are similar. It is only at very high flow rates (in excess of 100 l/min) that differences in resistive characteristics become evident (Figs 3.1 and 3.2). Resistance evaluations for continuous expiratory flows at low flow rates (from 5 - 70 l/min) are shown in Figures 3.3 and 3.4. Pressure-volume curves for each cartridge type respirator (Fig. 3.3) ranged from 0.03 - 0.22 Pa/l/sec. For two of the dust-mask type respirators (Moldex #3400, 3M #9920), resistances were comparable with the cartridge types (Fig.3.4). The Sundstrom respirator recorded the least resistance of all the devices evaluated (from 1.0 to 1.6 times greater than the breathing valve).

### **3.3.3 External Dead Space Measurements and Weights of the Respirators**

External dead space measurements for the respirators ranged from 150 -220 ml ( $\pm 1\%$ ) (Table 3.5). The facemasks of the respirators varied in size and shape, as did the positions of the inhalation and exhalation valves. The weights of the devices showed wider variation and ranged from 12 - 355 gm ( $\pm 1\%$ ) (Table 3.5). The facemask, cartridge(s), cartridge cover(s) and head straps were included in the assessment.

**Table. 3.4 Expiratory resistances (kPa/l/s) for respirators with twin and single exhalation valves at 85.0 l/min. Dust mask type respirators are also included.**

Model of Respirator	Number of Exhalation Valves	Expiratory Resistance (kPa/l/s)
Sundstrom SR90	2	0.09
Protector (Twin)	2	0.06
Protector (Single)	2	0.10
Norton 7700	1	0.14
Kemira Silner 12	1	0.22
Moldex 3400	1	0.06
3M 9920	1	0.06
3M 9900	-	0.05

**Table 3.5 Dead space and relative weights of the eight devices evaluated. Standard errors of measurement are given for dead space volumes and respirator weights.**

Respirator Type	Dead Space* (ml)	Weight+ (gm)
Kemira Silner 12	190 (3.0)	355 (1.0)
Norton 7700	180 (2.8)	340 (0.8)
Protector (Twin)	200 (3.2)	330 (0.7)
Protector (Single)	190 (3.0)	190 (0.5)
Sundstrom SR 90	200 (3.2)	305 (0.6)
Moldex 3400	220 (3.5)	48 (0.1)
3M 9900	185 (2.9)	12 (0.02)
3M 9920	150 (2.4)	30 (0.08)

\* Volume (standard error of measurement)

+ Weight (standard error of measurement)

### 3.4 Discussion

The pressures and resistances determined by these evaluations are comparable, if slightly lower, than evaluations undertaken by previous authors (Stemler and Craig, 1977; Louhevaara, 1984; Louhevaara *et al*, 1984; Louhevaara *et al*, 1986; Jette *et al*, 1990). Table 3.6, reviews the data on breathing resistances of air-purifying respirators from earlier studies and compares the results of the present study to them.

**Table 3.6 Comparison of inspiratory and expiratory breathing resistances of air-purifying respirators from earlier studies and the present study.** The range of pressures inside the facemask at a specified flow rate are listed as resistances.

Breathing Resistance <sup>#</sup> at airflow rate of 85 l/min <sup>+</sup>		Reference
Inspiratory (kPa/85l/min)	Expiratory (kPa/85l/min)	
0.3 - 0.5	0.2 - 0.3	Stemler & Craig (1977) Louhevaara <i>et al</i> (1984)
0.2 - 0.3	0.25 - 0.3	Louhevaara <i>et al</i> (1984)
0.25 - 0.3	0.5 - 0.7	Louhevaara <i>et al</i> 9(1986)
0.13 - 0.18 <sup>*</sup>	-	Jette <i>et al</i> (1990)
0.0 - 0.2 <sup>1</sup>	0.0 - 0.2 <sup>1</sup>	Jones (1991) <sup>1</sup>
0.05 - 0.11 <sup>1</sup>	0.01 - 0.1 <sup>1</sup>	Present Study <sup>1</sup> (3M, Moldex)
0.1 - 0.23 <sup>2</sup>	0.06 - 0.2 <sup>2</sup>	Present Study <sup>2</sup> (Norton, Protector, Sundstrom, Kemira)

# Resistances are usually expressed as kPa/l/s. Pressure inside the facemask at a specified flow rate is referred to in the above studies. The same convention is used for results in the present study.

+ continuous flow

\* recorded at airflow of 35 l/min

1 dust-mask type respirators

2 cartridge type respirators

The Table 3.6 provides evidence that there may have been some reduction in resistance values for respirators over the 15 year period documented (including the present study). It can be seen that most evaluations have been conducted on cartridge type air purifying respirators (Stemler and Craig, 1977; Louhevaara *et al*, 1984; Louhevaara *et al*, 1986; Jette *et al*, 1990) and it has been only recently that dust-mask type respirators have attracted attention (Jones, 1991). The results support studies by Louhevaara *et al*, (1984), (Table 3.2) in which inspiratory resistance was shown to be double expiratory resistance.

The studies by Stemler and Craig (1977) and Louhevaara *et al*, (1984) showed inspiratory resistances were higher than expiratory resistances. Later studies showed the converse (Louhevaara *et al*, 1986), or little difference (Louhevaara *et al*, 1985). In his 1984 study Louhevaara *et al*, examined a Kemira air-purifying respirator of the same model as was used for the current evaluation. Facemask pressures at 85 l/min were found to be 0.14 kPa (expiratory) and 0.30 kPa (inspiratory) (Table 3.2). The results of the present study (Table 3.6) are comparable to these values. The inspiratory pressures recorded by Louhevaara *et al*, (1984) are marginally higher than the range measured in the present study. This could possibly be explained by manufacturing modifications over the last 10 years to the filter medium (activated charcoal) which have improved the inspiratory resistance characteristics of air-purifying respirators (Lundin and Colton, 1988). The improvements have been undertaken presumably to comply with standards for inspiratory and expiratory resistance (e.g. AS 1716, 1991). Resistance values for flow rates below 30 l/min however were not recorded by Louhevaara *et al*, 1984. This seems an important omission as expiratory and inspiratory resistances at these lower flows would likely be experienced by many respirator users in industry (Louhevaara *et al*, 1984; Louhevaara *et al*, 1986). The condition of the filters used in these studies are not mentioned in the methodologies and it can only be assumed that they were new, clean filters.

There appears to be little physiological rationale to study resistance determinations of respirators in excess of 150 l/min. The measurement of flows of up to 300 l/min have

been included in the present study as they were measured by Louhevaara *et al*, (1984) and Louhevaara *et al*, (1986) and provide useful comparative performance data for devices used in New Zealand. The effect of turbulence at these higher flows on resistive characteristics has not been identified by the previous authors (Louhevaara *et al*, 1984; Louhevaara *et al*, 1986; Jette *et al*, 1990; Jones, 1991). For the purposes of the experiment, turbulent flows at these higher flow rates were considered acceptable.

The rationale for using reciprocating rather than continuous flows in this study, is to model more closely the events that occur during normal ventilation. This approach was first suggested by Cooper (1960) and, as yet, has not been followed up by later researchers. The results of the present study, whilst providing useful data on the dynamic characteristics of air flows during the breathing cycle, provide little additional information that would be of significant benefit to respirator designers and manufacturers. The data does indicate however variations in peak pressures inside the mask, primarily due to differences in inspiratory and expiratory valve construction and orientation, that is both the Sundtsrom SR 90 and Protector (Single) have a single cartridge filter anterior to the mouth and two exhalation valves at the side of the facemask, compared to the Protector (Twin) with two cartridge filters positioned at the side and the two exhalation valves anterior to the mouth.

The first comprehensive review of expiratory valves in respirators was conducted by Silverman *et al*, in 1943 for the U.S. Office of Scientific Research and Development. In this study, resistance to air-flow, dynamic and static leakage and opening pressure of expiratory valves were measured. The authors confirmed that the inspiratory and expiratory maximum air flows and minute volumes increased exponentially with increasing work rate and that the air flow curves obtained at various work rates were effected by the resistive characteristics of the respirators evaluated. Later, another study (Burgess and Anderson, 1967), examined the performance of valve types (described in the Introduction, section 1.2) and evaluated the performance factors of the valves isolated from the respirator assembly. The study showed a difference between expiratory resistances between respirators with single and twin expiratory

valves. This observation that respirators with twin exhalation valves offer less expiratory resistance at high flow rates than single valve respirators has direct relevance for designers and manufacturers of respirators. This observation was supported by evidence from the surveys of respirator use (Chapter 2), where the air-flow resistance of respirators was not a significant factor in respirator non-use (particularly in the South Island survey). The respirator in most common use there (Sundstrom SR 90) has been shown by this study, to have low inspiratory and expiratory resistances. The device has a twin exhalation valve system (Figure 3.1). The significance of these findings will be discussed in more detail in the General Discussion (Chapter 8).

In relation to disposable dust mask type respirators, Jones (1991) commented that:

" Despite the popularity of single-use disposable respirators, much remains unknown about the performance of these device. Little is known about the devices' resistance to breathing, cardiopulmonary effects and effects of heat stress".

The results of the present study indicated that the dust-mask type respirators evaluated exhibited little resistance over a wide range of flow rates, but the respirators with exhalation valves (Moldex #3400 and 3M #9920) tend to have similar resistive characteristics to the cartridge type respirators at moderate to higher flows (from 50 to 280 l/min). The data obtained on dust-mask type respirators, indicated that they induced very small expiratory breathing resistances ( $< 0.05$  kPa at an airflow rate of 40 l/min). This was also confirmed in the survey of respirator usage (Chapter 2) in which many wearers had a preference for the disposable dust-mask type due to its perceived low resistance

As the normal airway resistance of individuals range between 0.05 - 0.2 kPa at an airflow rate of 1.0 l/sec (Cotes, 1979), the values obtained in the present study, support the view that the additional resistance imposed by the respirator may contribute significantly to wearer acceptability, particularly at higher workloads (Louhevaara, 1984; Louhevaara *et al*, 1984; Jones, 1991). That is, the use of the respirator effectively doubles the normal airway resistance of an individual.



Of the cartridge type respirators, the pressure-volume diagrams for the Sundstrom device exhibited the lowest resistance of all those evaluated (Table 3.3 and Appendix 2, Figure A2.4). This respirator showed comparable resistance values to the dust-mask type respirators at low flow rates of up to 30 l/min (0.01 - 0.030 kPa/l/s). At higher flows (up to 60 l/min), pressure ranges from 25-60 Pa were recorded, (from 0.01 kPa/l/s up to 0.03 kPa/l/s) as Appendix 2 Figure A2.4. shows.

The external dead spaces of the cartridge and dust-mask types of respirators were surprisingly similar (mean 189.3 ml  $\pm$ 20.1 ml). These values are within the range of external dead space determinations of 36 to 1400 ml previously reported (Jones *et al*, 1971; Bartlett *et al*, 1972; Kelman and Watson, 1973; Stemler and Craig, 1977; Sackner *et al*, 1980; Harber *et al*, 1982; Louhevaara *et al*, 1984). The volume of 1400 ml was reported by Jones *et al* (1971) as the external dead space of self contained breathing apparatus (SCBA) used in emergency situations. However, it is likely that the volume referred to would be continuously filled with oxygen and not constitute the term 'dead space'. A large external dead space would increase the concentration of carbon dioxide in the inspired air and stimulate ventilation in order to maintain normal alveolar carbon dioxide tension.

The results of the present study indicate that most air-purifying respirators available in New Zealand increase external dead space volume in the order of 200ml, which effectively doubles the normal value for anatomical dead space of 150 ml (Cotes, 1979). Increased artificial dead space has been shown to lead to an increase in the alveolar carbon dioxide tension and in minute ventilation at rest and at work (Jones *et al*, 1971; Raven *et al*, 1979). It has been suggested that the additional effort of breathing against increased resistance and dead space may increase oxygen consumption and heart rate, particularly at higher work levels (Jones *et al*, 1971; Kelman and Watson, 1973; Bartlett *et al*, 1972; Sackner *et al*, 1980; Louhevaara *et al*, 1984).

The weights of the respirators were remarkably varied (from 12 - 355 gm). The number and size of the interchangeable cartridges contributed most to the differences

in weight. The earlier studies of Stemler and Craig (1977) and Louhevaara *et al*, (1984) report respirator weights of between 500 and 1000 gm. Louhevaara *et al* (1984) measured the weight of the same device (Kemira Silner 12, 1984) as 500g. It is apparent that there has been a reduction in the respirator weight from that time (present study Table 3.5, 355(1.0)gm). Excluding the dust-mask respirators, the weights of the devices appear to have been reduced from those previous studies, indicating some possible advance in the use of lighter material for the facemask, cartridges or a combination of both. The weight of the device was seen as a reason for non-use in the respirator use survey (Chapter 2) and is an important factor in the selection of suitable respirators for particular work environments or activities.

#### 3.4.1 Possible Sources of Error

In addition to systematic and random measurement errors, other possible sources of error included:

- (i) the potential for the airtight seal between the respirator face mask and the dummy to be weakened during the test. The pressures measured would be compromised. In order to evaluate leakage occurring during the test, the same pressure-decay evaluation was completed after each test as was conducted prior to the test, to ensure the adequacy of the seal between the mask and the dummy.i.e negative pressure induced and maintained for 30 seconds with inspiratory and expiratory valves sealed.
- (ii) the turbulence created at high flow rates (>100 l/min) through the 20mm mouth tube could affect the orientation and position of the inspiratory and expiratory valve diaphragms, therefore effecting the pressures measured. All of the respirators tested had simple flap-type valve diaphragms, a visual check of the valve during the test was made to ensure it was not abnormally positioned.

In summary, previous studies have identified breathing resistances, external dead space and additional weight as key factors in wearer work performance. These factors were

measured for a variety (8) of commonly used air-filtering respirators in New Zealand industry. Reciprocating in addition to continuous airflows were used to examine air-flow resistances through the exhalation/inhalation valve systems. Data from the reciprocating flows provided little additional information on flow characteristics of respirators. Valve 'noise' (pressure fluctuations due to valves opening and closing) was identified in three of the devices. A difference in airflow resistance was seen between high and low efficiency respirators and between respirators with twin and single exhalation valve systems. The respirators examined had similar external dead space values, but device weights varied widely. It was found that weight of respirators has decreased markedly from reports of earlier studies (Louhevaara *et al*, 1984).

In conclusion evidence from the present study suggests that:

- (i) Of the eight respirators assessed, the inspiratory and expiratory resistances measured in the present study were low in comparison to earlier studies and below the recommended standards (AS 1716, 1991) for acceptable breathing resistance.
- (ii) Expiratory resistances of respirators with two exhalation valves were lower than those with single valves.
- (iii) Inspiratory resistances of all respirators evaluated were higher than expiratory resistances.
- (iv) The use of reciprocating flows provided little additional information on flow characteristics apart from identifying a possible contribution the valves make to sensations of resistance.
- (v) Fluctuations in peak pressures were detected in three respirators (Kemira and both Protector respirators) as a result of valve opening and closing pressures.
- (vi) The respirators investigated had similar external dead space volumes.
- (vii) The weights of the respirators varied widely, with the disposable devices weighing substantially less than the cartridge type devices.

## CHAPTER 4

### 4.0 LABORATORY STUDIES ON THE PHYSIOLOGICAL COSTS OF WEARING RESPIRATORY PROTECTIVE EQUIPMENT

#### 4.1 Introduction

The extensive use of respiratory protective devices during the Second World War prompted detailed studies of their impact on the wearer (see Silverman *et al* 1951). In a series of experiments this author demonstrated that both the pattern of breathing and oxygen consumption were modified by respirator usage during short term exercise on a cycle ergometer (Silverman *et al*, 1943; Silverman *et al*, 1945; Silverman *et al*, 1951). Subsequent studies have largely confirmed this observation (see James 1976; Raven *et al*, 1979; Louhevaara, 1984 for reviews), although there is still no definitive picture as to what are the most important physiological effects of respirator usage.

Industrial filter type respirators increase the respiratory dead space (James *et al*, 1971; Kelman and Watson, 1973; Sackner *et al*, 1980 and Harber *et al*, 1982; Chapter 3 of this study) and airways resistance of the wearer (Jones *et al*, 1971; Raven *et al*, 1977; Stemler and Craig 1977; Harber *et al*, 1982; Louhevaara, 1984; Chapter 3 of this study). Several groups have investigated the effects of increased dead space and airflow resistance on the pattern of breathing either by simulating the effects of respirators using external resistances and dead space (Silverman *et al*, 1951; Harber *et al*, 1984; Shimozaki *et al*, 1988) or by using modified respirators (Raven *et al*, 1981a, 1981b; Louhevaara *et al*, 1984). The former approach has the advantage that inspiratory resistance, expiratory resistance and dead space could be varied independently and tightly controlled.

During submaximal exercise, whilst wearing a respirator, minute ventilation ( $\dot{V}_{\text{min}}$ ) has been shown to be directly proportional to the increase in dead space volume (Bartlett *et al*, 1972); tidal volume ( $\dot{V}_t$ ) in one study has been shown to increase to as much as

70% of an individual's vital capacity (Kelman and Watson, 1973). In addition, as discussed in Chapter 1 (section 1.4.3) one study proposed that the energy cost of breathing is increased by respirator usage (Morgan, 1983), however, this has not been regularly confirmed (Harber *et al*, 1984; Louhevaara *et al*, 1984; Jette *et al*, 1990).

Both increased inspiratory or expiratory resistance have been shown to decrease breathing frequency at submaximal work levels (Tabakin and Hanson, 1960; Levy *et al*, 1961; Gee *et al*, 1968; Flook and Kelman, 1973; Harber *et al*, 1982). However, increased inspiratory resistance only marginally affected tidal volume which remained unchanged or slightly increased in young subjects (Flook *et al*, 1973; Gee *et al*, 1968; Harber *et al*, 1982) and reduced in older individuals (Dressendorfer *et al*, 1977; Harber *et al*, 1982). Only at high work rates ( $80\% \dot{V}_{O_2 \text{ max}}$ ) where breathing frequency was reduced by 30-45% was  $\dot{V}_{O_2}$  affected (Dressendorfer *et al*, 1977). However, those conditions ( $80\% \dot{V}_{O_2 \text{ max}}$ ) are extreme and unlikely to be encountered in general industrial situations. The abrupt decrease in the frequency of breathing caused by an increase in expiratory resistance (Tabakin and Hanson, 1960; Levy *et al*, 1961) leads to a reduction in  $\dot{V}_{O_2}$  and  $\dot{V}_{CO_2}$ , i.e. hypoventilation (Gee *et al*, 1968). Contrary to the view of Beckett and Billings (1985), two studies indicate that increased expiratory resistance constitutes the most important resistive load on the respiratory system (Gee *et al*, 1968; Demedts *et al*, 1973). In 'filter-type' air purifying respirators the major expiratory resistance is caused by a simple one way valve (refer Chapter 1). The possibilities for further improvements and modifications to the valve systems appear to be areas that will benefit from this and future research.

The importance of increased inspiratory resistive loading has been identified as a major cause of respirator non-use by several authors (Love *et al*, 1977; Beckett and Billings, 1985; Louhevaara, 1984; Chapter 2 of the present study). The increased inspiratory resistance has been reported as being due to poor maintenance of the air-filtering system (either the filtering material or carbon cartridges) caused by excessive build up of contaminant (Love *et al*, 1977; Ballantyne and Schwabe, 1981; Lundin and Colton, 1991). These findings are also supported with evidence from Chapter 2 of the present study that indicated that little information and training was provided to

respirator users on the maintenance of the devices. The present study is concerned with the physiological costs associated with inspiratory rather than expiratory resistive load.

Whilst some information exists about the effects of respirators on breathing, 'such observations have not been correlated with surveys of respirator tolerance in the workplace' (Beckett and Billings, 1985). Pulmonary diffusion capacity does not appear to alter with short term respirator use (Gee *et al*, 1968), although it has been suggested that the higher negative pressures required during inspiration might be expected to generate pulmonary oedema (Raven *et al*, 1979). Additionally, it has been suggested the high air pressures involved in breathing through a respirator might modify the cardiovascular function by effecting venous return to the heart (Raven *et al*, 1979; Louhevaara, 1984; Jones, 1991). Observations on the systemic circulation are disparate. Respirator usage has been shown to decrease heart rate (Van huss *et al*, 1967), have no effect on heart rate (Thompson and Sharkey, 1966; Chaterjee, 1969; Raven *et al*, 1977; Harber *et al*, 1982; Harber *et al*, 1984; NIOSH 1986), or an increase in heart rate (Shephard, 1962; Hermansen *et al*, 1972; Dressendorfer *et al*, 1977; Louhevaara and Tuomi, 1984; Louhevaara *et al*, 1985). Also, it has been suggested that changes in cardiac output and in lung volumes and pressures could affect ventilation/perfusion ratios in the lung (Tabakin *et al*, 1965). The effect of respirators on workers with drug controlled cardiovascular or metabolic disorders, i.e. hypertension, myocardial insufficiency, diabetes etc. has never been investigated (refer review by Raven *et al*, 1979). It is apparent that the respirator produces a variety of stresses on the body some of which are readily measurable and others that are more difficult to evaluate.

The warm 'microclimate' of the inside of the face mask also produces unpleasant thermal sensations, only partially explained by reduced respiratory heat loss (Nielsen *et al*, 1987a, 1987b). It has been suggested that the most 'bothersome' aspect of wearing respiratory protection was the excessive heat inside the devices (Hodous *et al*, 1989). Recent studies have attempted to quantify subjective assessments of discomfort associated with a range of ambient air and skin temperatures whilst

wearing respirators (Neilsen *et al*, 1987a, 1987b; White *et al*, 1989; Gwosdow *et al*, 1989; DuBois *et al*, 1990; Jones 1991). The studies concluded that skin temperatures under the respirator mask in excess of 34.5°C, and air temperatures greater than 33°C, decreased respirator acceptability markedly.

The object of this study is to determine whether wearing a respirator (at rest and at work) imposed an additional physiological strain on an individual. In doing so, it was therefore important to determine which measures of strain were appropriate and how best could any significant changes be detected. The theoretical framework for the study was introduced in Chapter 1 (section 1.6) and illustrated in Fig.1.3. The essential feature of the model is the interrelation of the stressors on the individual producing a strain, which can be measured by standard physiological methodologies.

The experimental design of the study involved (i) the control of environmental influences and work demands and (ii) by varying the respirator physical characteristics (by artificially increasing the resistance of the device), any resultant change in the physiological variables selected may therefore be detected and measured. Physiological variables that were identified in Chapter 1 as important measures of strain (Raven *et al*, 1979; Louhevaara, 1984; Jones, 1991) included changes in mean heart rate (mean HR), mean oxygen consumption (mean  $\dot{V}O_2$ ), mean carbon dioxide production (mean  $\dot{V}CO_2$ ), mean minute ventilation (mean  $\dot{V}_{min}$ ) and the respiratory exchange ratio (R). In addition, perceived difficulty breathing (PDB) was included as a psycho-physiological index of dyspnea (Morgan and Raven, 1985). External environmental influences (temperature, humidity and air velocity) were not able to be controlled during the experiment.

## 4.2 Materials, Method and Equipment

### 4.2.1 Subjects

A series of experiments was carried on twelve fit adult volunteers. Prior to the experiment, maximal oxygen consumption ( $\dot{V}O_2 \text{ max}$ ) for each subject was estimated

from heart rates at sub maximal work loads using the Astrand nomogram (Astrand, 1960). The experiments consisted of the subjects working at a moderate level (approximately 50%  $\dot{V}O_2$  max) on a cycle ergometer, whilst wearing a respirator of known physical characteristics. Each received token remuneration for participation.

#### 4.2.1.1 Determination of subjects maximal oxygen uptake and maximal heart rate

This involved a protocol in which the subject worked using a cycle ergometer (Monarch 818) at progressively increasing workloads (from resting to 50W, 100W and 150W with a pedal frequency of 60 revs/min). Measurements of heart rate were made continuously throughout the test. Ventilation ( $\dot{V}min$ ), inspired and expired oxygen and carbon dioxide concentrations were measured corresponding to each workload, at 3 minute intervals during the course of the test, using the standard Douglas bag technique (Astrand, 1960). Following the final workload measurements, the subject was monitored through a 'warm down' recovery period which lasted between 3-5 minutes. Maximal values for oxygen consumption are then able to be estimated from the nomogram developed by Astrand, (1960). Maximum heart rate was determined by the predictive formula  $210 - 0.66$  the subjects age (Jones, 1988). Maximal values for the subjects and their characteristics are given in Table 4.1. Prior to the experiment subjects were fully informed as to its objectives and methods that would be used and an informed consent document was signed in accordance with the protocol approved by the Massey University Human Ethics Committee.

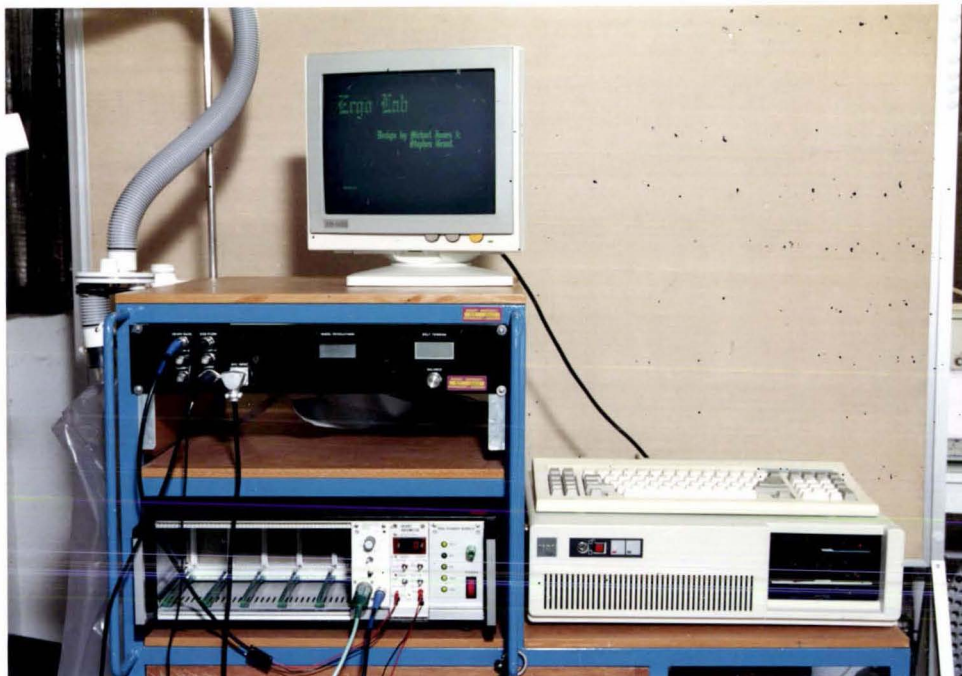
#### 4.2.2 Experimental Design

Each subject was asked to perform a series of exercise tasks at approximately 50% of their predicted  $\dot{V}O_2$  max either using a high velocity breathing valve and standard Douglas bag system (Morgan, UK) or wearing a respirator modified to allow collection of expired gas through the exhalation valve (Raven *et al*, 1981b).





**Plate 4.1** Experimental apparatus used in the determination of the physiological cost of respirator use. This includes an ergometer, breathing valve, gas analyser and Douglas Bag, computer application for data collection and J-Rak heart rate monitor.



**Plate 4.2.** J-Rak system and data collection equipment for physiological measurements of respirator use. Douglas Bag system for expired gas collection and analysis shown on the left.

7	I Can't Breathe
6	
5	I Am Not Getting Enough Air
4	
3	I Am Starting To Breathe Harder
2	
1	My Breathing Is O.K. Right Now

**Fig. 4.1** Seven point psychophysical category scale (Difficulty Breathing Scale) used to quantify respiratory difficulty (after Morgan and Raven, 1985).

#### 4.2.2.1. Calibration of Equipment

**Heart Rate Monitor:** Heart rates were monitored throughout the maximal oxygen uptake estimations and the experimental trials, using a standard isolated ECG amplifier (Neurolog NT117, Neomedic Sytems, Sydney, Australia) and cardiac ratemeter (JRAK, Australia) (Plate 4.2). The ratemeter was calibrated using the internal standards of 25 and 300 beats per minute, and measurements were shown to be in the tolerance range of  $\pm 1.0\%$ .

**Gas Analyser:** Expired gas analysis was undertaken using a Datex Normocap carbon dioxide and oxygen analyser, calibrated with a gas standard (3%  $\pm 0.1\%$  carbon dioxide, 17%  $\pm 0.1\%$  oxygen, balance nitrogen, NZIG). Calibration data for Datex gas analyser are given in Appendix 3. Twenty one samples were taken over a period of five days. Means and standard deviations for the samples were tabulated and standard errors of measurement calculated. Metabolic rate was calculated using standard formulae from the expired gas composition and volume (Morgan, 1985). A standard dry gas meter with water bath was used to measure gas volumes (reading accuracy of  $\pm 0.1$  litres).

**Cycle Ergometer:** A Monarch 818 cycle ergometer was modified to enable the work done by the subject to be measured in absolute terms. This involved the attachment of a force transducer to measure the tension of the braking belt (force) and a Hall effect transducer and interface to count wheel revolutions (distance). Plate 4.1. (Force transducer and revolution counter, linearity to 0.1 rev). The ergometer was calibrated using a 5 kg weight attached to the belt drive (readability to within 3 Watts determined by repeated measures).

#### 4.2.3 Experimental Measurements and Technique

For each situation, a steady state expired gas sample was obtained and analysed by conventional means (after Astrand, 1984), with and without wearing the respirator:

1. at rest and

2. during exercise at the predetermined rate (approx 50%  $\dot{V}O_2$  max).

The 'steady state' was deemed to be achieved when four consecutive heart rate measurements were recorded  $\pm 2$  b/min over a period of a minute. The subject was seated on the ergometer without the respirator and an expired gas sample was taken using the high velocity breathing valve (P-338 Triple "J", Warren E. Collins Inc.) and a standard Douglas bag (Morgan, UK) (Plate 4.2). Oxygen concentrations from inspired air were recorded initially, then an expired air sample was taken over a period of 2 minutes. The oxygen and carbon dioxide concentrations in the sample were recorded using the gas analyser (Datex Normocap, London, UK), and the expired air volume measured with a dry gas volume meter. The respiratory hose system from the subject and to the gas analysis equipment was visually checked to detect leakages before each experiment. During the experiment a check was made of the hose connections to ensure no leakages occurred.

The measurement procedure was then repeated with the respirator on the subject's face. This was achieved by collecting expired gas through a modification to the exhalation valve of the respirator. The outer ring of the exhalation valve was fitted with a standard hose connection collar which enabled the connecting hose to be attached. Through this, expired air could be collected, and this sample analysed for oxygen and carbon dioxide concentrations, and sample volume. The sample was similarly taken over 2 minutes. In addition, the subject was asked to subjectively assess the difficulty breathing on a visual analogue scale (after Morgan and Raven, 1985) (Fig.4.1). The odd numbers are anchored with verbal descriptions and the scale was placed before the subjects and ratings were obtained before the end of the measurement period.

The study was performed over a series of three sessions, each of which were three days apart. Variables monitored were heart rate, external work, inspired and expired oxygen, inspired and expired carbon dioxide and perceived difficulty breathing. Metabolic rate was calculated from gas composition. The effects of three differing respirator conditions were evaluated at each experimental trial. These conditions included :

- A. No respirator. (Expired gas was collected by the use of the high velocity breathing valve - Warren E. Collins Inc. P-338 Triple"J")
- B. Respirator in its normal configuration. Described as an ori-nasal face mask with twin cartridges - Kemira Silner 12. Cartridges were specific for protection against organic vapours. (Expired gas was collected through modification to exhalation valve).
- C. Respirator with additional resistive load. The same as used above, with one inhalation valve occluded to increase the inspiratory resistive load.

Gas analysis whilst wearing the respirator was possible by a modified exhalation valve connection of the test respirator. Data were collected and integrated using a computer programme (Ergolab 2) designed and developed in association with Information Systems research and development staff, Massey University, Palmerston North (See Appendix 3 for details). The system receives output data from:

- (i) Datex Normocap carbon dioxide and oxygen analyser
- (ii) Dry Gas volume meter
- (iii) ECG amplifier and cardiac ratemeter
- (iv) Force transducer and revolution counter from the cycle ergometer
- (v) Time signal

The programme collected the output data and used a sub-routine to display the data in an acceptable format for subject monitoring throughout the experiment and experiments are identified by test number and Douglas bag number within each test. Subject details, including subject name, date, weight, height, room temperature, atmospheric pressure were also recorded. In addition, correction factors for temperature and pressure were generated. Each test file comprised the collection of data for each douglas bag assessment which is stored on disc for importation to a spreadsheet (VP-Planner, Paperback Software, 1989) for subsequent analysis.

The percent relative workload (%RW) index was used in the present study, firstly as the values give estimates of individual workloads defined as the mean oxygen

consumption value as a percentage of the estimated maximum oxygen consumption and secondly for comparison with other studies that have used estimations of subjects' workloads (Astrand *et al*, 1973; Fordham *et al*, 1978; Goldsmith *et al*, 1978; Louhevaara *et al*, 1984; Louhevaara *et al*, 1985).

#### 4.2.4 Environmental Variables

The thermal environment was measured before and after each experimental trial. Ambient air temperature (dry bulb and wet bulb temperatures) and relative humidity were measured using a standard whirling hygrometer (Cassella, England). Air velocity was measured using a hot wire anemometer (TA 3000, Airflow Instruments, UK). It is acknowledged that a Kata thermometer would have been the preferable instrument in the circumstances, however, the device was not available for the entire duration of the experimental trials and the thermal anemometer was used as an alternative. The objective was to identify large movements of air that may adversely effect subject performance rather than to quantify the very small air flows in the laboratory environment. It was not possible, with the experimental space available to regulate any of the variables in a controlled way.

#### 4.2.5 Statistical analysis

The data was analysed using the analysis of variance technique of Latin Squares. This involved random allocation of every treatment category (respirator condition above), to a randomised block. As the experiment is replicated three times, a 3 by 3 randomised block is created. Each respirator condition occurs once in each row and once in each column (A, B or C). The analysis allows each classification to be examined independently of each other one. Analysis of variance using a MANOVA (3 by 3) Latin Square design was undertaken using SPSS/PC+ Version 4.0.1. (Microsoft Corporation, 1989). F values were calculated for the variables: heart rate, oxygen consumption, carbon dioxide production, minute ventilation, respiratory exchange ratio and perceived difficulty breathing. Respiratory exchange ratios were calculated to determine the extent of hyper- or hypo-ventilation experienced by

subjects.

A	B	C
B	C	A
C	A	B

The practical usefulness of Latin squares in experimental design is restricted by (i) the condition that the number of treatments must be the same as the number of nuisance or confounding factors, and (ii) one must assume that there is no interaction between factors. It is suggested that the Latin square design be used with caution since the presence of interactions can invalidate the results (Dixon and Massey, 1969).

However, there are significant reasons for using the Latin square design in a variety of experimental situations. Firstly, the design is particularly appropriate for comparing two treatment means in the presence of two sources of extraneous variation, and secondly, the analysis is quite simple. In addition, we can compare the relative efficiency of the Latin square design to the completely randomised design. This in effect provides an important indicator of the precision for comparing treatment means in a given experiment.

The initial analysis of data for Latin square designs concentrated on the subject by subject variation, which was useful in identifying and quantifying statistically significant variations in the individual's physiological and psycho-physiological parameters. The subsequent analysis of variance and analysis of means of replicated latin squares was undertaken on the pooled data. This allowed more detailed examination of main and nested effects and their interactions.

#### 4.2.5.1 Analysis of Variance (Subject by Subject)

The statistical technique utilised in the subject by subject analysis of variance is derived from the SPSSx Users Guide (Microsoft Corporation, 1989). The following

MANOVA specification was used to analyse the 3 x 3 Latin square:

```
DATA LIST FIXED/ TYPE 1 DAY 2 (XYZ) 3, 3-4, 3-5 RUN 6.
  BEGIN DATA.
    11...1
    12...3
    13...2
    21...2
    22...1
    23...3
    31...3
    32...2
    33...1
  END DATA.
  MANOVA XYZ BY TYPE (1,3) DAY (1,3) RUN (1,3) / DESIGN = TYPE
  DAY RUN.
```

The test of significance for the variable in question (XYZ) used the UNIQUE sums of squares. Results are expressed in an analysis of variance table and significance of F values determined using standard methods ( $P < 0.05$ , 0.01, 0.001).

#### 4.2.5.2 Analysis of Variance of Total Population (Pooled Data)

As suggested by Munford (1994) (Appendix 5), in an experimental design with replicated Latin squares, the nested effects (rows and columns within squares effects) are normally defined as random, whereas the main effects (Latin square replicates and treatment effects) are defined either as random or as fixed. In the analysis of variance that was undertaken, the test of significance assumed that the treatment effects were fixed. The analysis of variance of replicated Latin squares used the following data sources:

- All treatment totals
- Sums of treatments (A,B and C)
- Sums of squares of Days, Runs and Treatments

The rationale for undertaking the secondary analysis of variance involved pooling the data in order to increase the number of degrees of freedom afforded by the technique. The degrees of freedom with the pooled analysis increased from 8 to 32 or 34. Since



larger samples provide estimates of greater precision, we can attain any stated precision by taking samples sufficiently large. i.e. as the sample size increases the t-distribution becomes indistinguishable from the normal distribution (Dixon and Massey, 1969). The disadvantage of using the analysis of variance of the pooled data is that the precise advantages of the Latin square in controlling individual external sources of variation are lost.

### 4.3 Results

The characteristics of the twelve male volunteer subjects, in terms of their age, height, weight, maximal oxygen consumption and maximal heart rate are shown in Table 4.1.

**Table 4.1 Physical characteristics of twelve volunteer subjects including means and standard deviations.**

<u>Subject</u>	<u>Age(vrs)</u>	<u>Height(cm)</u>	<u>Weight(kg)</u>	<u><math>\dot{V}O_{2 \max}^*</math></u>	<u>HRmax<sup>+</sup></u>
1	21	180	92	38.04	196
2	23	178	91	39.56	195
3	32	177	79	55.69	189
4	20	187	89	37.07	197
5	19	180	86	38.37	198
6	20	168	60	46.66	197
7	21	164	63	38.09	196
8	23	176	82	58.54	195
9	28	185	82	43.90	191
10	32	177	75	59.12	189
11	25	170	67	49.25	194
12	30	185	85	60.24	190
mean	24.5	177.3	79.3	47.04	193.9
s.d.	4.8	7.0	10.8	9.2	3.2

\* Expressed in ml/min/kg (estimated)

+ Maximal heart rate calculated by the formula  $210 - 0.66 \times \text{age}$  (Jones, 1988).

The group of subjects was young (mean age  $24.5 \pm 4.8$ ) and displayed moderate to high levels of cardiorespiratory fitness (mean  $\dot{V}O_{2 \max}$  47.04 (9.2) ml/min/kg; mean

maximal heart rate 193.9(3.2). Environmental conditions ranged from 18.0-20.5°C dry bulb temperature, 15.0-17.4°C wet bulb temperature and 60-75% relative humidity. Air velocity in the experimental room was below 0.01 m/sec during the trials. The subjects wore light athletic clothing (T-shirt, shorts or track pants) and running shoes with sports socks. The subject wore the same clothing on each experimental trial day. The trials were scheduled at the same time each day for each subject (morning or late afternoon). The subjects did not eat or drink beverages before the experiment.

#### 4.3.1 Wearing a Respirator at Rest (5.0-11.3 %RW)

The subject by subject analysis of variance showed significant ( $P < 0.10$ ) changes in gas exchange and minute ventilation in 4 of the 12 subjects, although no clear trend was evident. The changes were evident between days, between trials (runs) and as a consequence of respirator use (Tables 4.2, 4.3, 4.4).

No variation in the heart rates were recorded in subjects between days (Table 4.2), or between runs (trials) (Table 4.3) or as a consequence of respirator use (Table 4.4). Perceived difficulty breathing was unaltered due to respirator use.

Two subjects (4,5) showed reductions in oxygen consumption at rest and one subject (6) showed an increase in  $\dot{V}O_2$  and  $\dot{V}CO_2$  between days (Table 4.2). Between run changes were recorded in four subjects minute ventilation (4,9,10) and  $\dot{V}O_2$  (1) (Table 4.3). Changes due to respirator use were seen in five subjects and included increases in  $\dot{V}O_2$  (1,9),  $\dot{V}CO_2$  (9),  $\dot{V}min$  (3,9,10) and perceived difficulty breathing (3,12) (Table 4.4). The perception of difficulty in breathing with a respirator at rest caused no discernable discomfort to the remaining subjects. Values on the Perceived Difficulty Breathing scale of 1 or 2 (my breathing is O.K. right now) were common to most subjects at rest.

The analysis of variance of the replicated latin squares of the total population (pooled data) at rest however, showed contrasting results. For resting values, no significant variances were shown for between days (cols/sqrs) or between runs (rows/sqrs).

However, the analysis did show a treatment effect for heart rate (rest) ( $P < 0.05$ ) and perceived difficulty breathing ( $P < 0.001$ ) (Table 4.8).

#### 4.3.2 Wearing a Respirator at Work (25.0-64.0 %RW)

At work changes in a number of variables were recorded (Tables 4.5 - 4.7). Of significance were the subjects assessment of their perceived difficulty breathing (PDB) whilst wearing the respirator. Most indicated a significant ( $P < 0.05$ ) increase in difficulty.

Eleven subjects recorded individual variation between days when working (Table 4.5). However, no overall pattern or trend was obvious. They included increased (2) and decreased HR (5,8,9); increased (1) and decreased  $\dot{V}O_2$  (5,10,11,12); increased (7,8,10) and decreased (5,12)  $\dot{V}CO_2$ ; increased (7,8) and decreased (5,12) minute ventilation; increased (4) and decreased (6,9) R and decreased perceived difficulty breathing (1).

Variation occurred less frequently (5 subjects) between runs or trials when at work (Table 4.6); increased HR (4); decreased  $\dot{V}O_2$ ,  $\dot{V}CO_2$  and  $\dot{V}_{min}$  (2,7,12); increased R (6). However, more variation became evident with the increasing load imposed by differing configurations of respirator (Table 4.7). At moderate workloads (25-64%  $\dot{V}O_{2\ max}$ ), two subjects (9,10) recorded significant variations in oxygen consumption and carbon dioxide production (9,12) as a result of the varying conditions of the respirator. Three further subjects recorded significant increases in heart rate (8), minute ventilation (12) and respiratory exchange ratio (6) respectively, as a result of the respirator type.

Ten of the twelve subjects, indicated that the changing conditions imposed on them by the respirator, significantly ( $P < 0.05$ ) increased their perceptions of difficulty breathing (Table 4.7). Three subjects found the exercise regimen whilst wearing the respirator very unpleasant, and were near the stage of removing the device at the conclusion of the trials. These findings are significant in the light of data collected by Louhevarra *et al*, (1985), who measured the cardiorespiratory strain in jobs which

require the regular use of respirators, and found that the relative aerobic strain of the work (construction, foundry, shipyard and metal industries) ranged from 12 to 57% of the estimated maximal oxygen uptake. The moderate workloads (25-64%  $\dot{V}O_{2\max}$ ) experienced by subjects in this study allow comparison with those measured by Louhevaara *et al*, (1985).

The analysis of variance for the pooled data did show a between day effect for heart rate and minute ventilation (Table 4.8), but no between run effect was evident. Indicating possibly, a relative consistency of experimental technique.

A treatment effect was significant for heart rate ( $P<0.001$ ), carbon dioxide production ( $P<0.05$ ) and perceived difficulty breathing ( $P<0.001$ ).

**Table 4.2 Analysis of MANOVA Latin Square (3 by 3) variable by Day for subjects at rest.** Changes between days to gas exchange and minute ventilation are seen in 4 of the subjects. Percentage relative workload (%RW) determined by method used by Fordham *et al*, (1978). Perceived difficulty breathing (PDB) as developed by Morgan and Raven (1985) and given in Fig 4.1.

DAY - REST							
Subject	HR	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}_E$	R	PDB	%RW <sup>#</sup>
1	-	-	-	-	-	-	10.8
2	-	-	-	-	-	-	7.1
3	-	-	-	-	-	-	5.0
4	-	** <sub>-</sub>	-	-	-	-	7.7
5	-	* <sub>-</sub>	-	-	-	-	9.1
6	-	** <sub>+</sub>	** <sub>+</sub>	-	-	-	9.7
7	-	-	-	-	-	-	11.3
8	-	-	-	-	-	-	11.0
9	-	-	-	-	-	-	9.8
10	-	-	-	** <sub>+</sub>	-	-	10.2
11	-	-	-	-	-	-	8.8
12	-	-	-	-	-	-	10.5

#      Mean  $\dot{V}O_2 / \dot{V}O_{2 \text{ max}}$  %  
\*\*\*    P<0.01  
\*\*      P<0.05  
\*        P<0.10  
+        indicates significant increase  
-        indicates significant decrease

**Table 4.3 Analysis of MANOVA Latin Square (3 by 3) variable by Run for subjects at rest.** Between trial changes to gas exchange and minute ventilation are seen in 4 subjects.

RUN - REST							
Subject	HR	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}e$	R	PDB	%RW <sup>#</sup>
1	-	**+	-	-	-	-	10.8
2	-	-	-	-	-	-	7.1
3	-	-	-	-	-	-	5.0
4	-	-	-	*+	-	-	7.7
5	-	-	-	-	-	-	9.1
6	-	-	-	-	-	-	9.7
7	-	-	-	-	-	-	11.3
8	-	-	-	-	-	-	11.0
9	-	-	-	*-	-	-	9.8
10	-	-	-	*+	-	-	10.2
11	-	-	-	-	-	-	8.8
12	-	-	-	-	-	-	10.5

#      Mean  $\dot{V}O_2$ /  $\dot{V}O_2$  max %

\*\*\*    P<0.01

\*\*      P<0.05

\*        P<0.10

+        indicates significant increase

-        indicates significant decrease

**Table 4.4 Analysis of MANOVA Latin Square (3 by 3) variable by Type (of respirator) for subjects at rest.** Changes due to respirator use are seen for gas exchange and perceived difficulty breathing in 5 subjects.

TYPE OF RESPIRATOR - REST							
Subject	HR	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}E$	R	PDB	%RW <sup>#</sup>
1	-	**+	-	-	-	-	10.8
2	-	-	-	-	-	-	7.1
3	-	-	-	*+	-	**+	5.0
4	-	-	-	-	-	-	7.7
5	-	-	-	-	-	-	9.1
6	-	-	-	-	-	-	9.7
7	-	-	-	-	-	-	11.3
8	-	-	-	-	-	-	11.0
9	-	*+	**+	***+	-	-	9.8
10	-	-	-	*+	-	-	10.2
11	-	-	-	-	-	-	8.8
12	-	-	-	-	-	**+	10.5

# Mean  $\dot{V}O_2 / \dot{V}O_{2\text{ max}}$  %  
\*\*\* P<0.01  
\*\* P<0.05  
\* P<0.10  
+ indicates significant increase  
- indicates significant decrease



**Table 4.5 Analysis of MANOVA Latin Square (3 by 3) variable by Day for subjects at work.** Changes are seen in 11 of the 12 subjects between days for heart rates, gas exchange and perceived difficulty breathing.

DAY - WORK							
SUBJECT	HR	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}e$	R	PDB	%RW <sup>#</sup>
1	-	* <sub>+</sub>	-	-	-	** <sub>-</sub>	64
2	** <sub>+</sub>	-	-	-	-	-	46
3	-	-	-	-	-	-	41
4	-	-	-	-	** <sub>+</sub>	-	30
5	* <sub>-</sub>	** <sub>-</sub>	** <sub>-</sub>	** <sub>-</sub>	-	-	56
6	-	-	-	-	** <sub>-</sub>	-	25
7	-	-	* <sub>+</sub>	** <sub>+</sub>	-	-	34
8	* <sub>-</sub>	-	** <sub>+</sub>	* <sub>+</sub>	-	-	56
9	** <sub>-</sub>	-	-	-	* <sub>-</sub>	-	54
10	-	* <sub>-</sub>	* <sub>+</sub>	-	-	-	52
11	-	* <sub>-</sub>	-	-	-	-	49
12	-	* <sub>-</sub>	** <sub>-</sub>	** <sub>-</sub>	-	-	53

# Mean  $\dot{V}O_2 / \dot{V}O_2$  max %

\*\*\* P<0.01

\*\* P<0.05

\* P<0.10

+ indicates significant increase

- indicates significant decrease

**Table 4.6 Analysis of MANOVA Latin Square (3 by 3) variable by Run for subjects at work.** Changes in heart rates and gas exchange are seen between trials for 5 subjects.

RUN - WORK							
SUBJECT	HR	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}E$	R	PDB	%RW <sup>#</sup>
1	-	-	-	-	-	-	64
2	-	-	*-	-	-	-	46
3	-	-	-	-	-	-	41
4	**+	-	-	-	-	-	30
5	-	-	-	-	-	-	56
6	-	-	-	-	**+	-	25
7	-	**-	**-	**-	-	-	34
8	-	-	-	-	-	-	56
9	-	-	-	-	-	-	54
10	-	-	-	-	-	-	52
11	-	-	-	-	-	-	49
12	-	-	-	*-	-	-	53

# Mean  $\dot{V}O_2$ /  $\dot{V}O_2$  max %  
\*\*\* P<0.01  
\*\* P<0.05  
\* P<0.10  
+ indicates significant increase  
- indicates significant decrease

**Table 4.7 Analysis of MANOVA Latin Square (3 by 3) variable by Type (of respirator) for subjects at work.** Changes are seen in heart rate and gas exchange in 5 of the subjects, perceived difficulty breathing is shown to be effected in 10 of the 12 subjects.

TYPE OF RESPIRATOR - WORK							
SUBJECT	HR	$\dot{V}O_2$	$\dot{V}CO_2$	$\dot{V}e$	R	PDB	%RW <sup>#</sup>
1	-	-	-	-	-	**+	64
2	-	-	-	-	-	-	46
3	-	-	-	-	-	*+	41
4	-	-	-	-	-	**+	30
5	-	-	-	-	-	**+	56
6	-	-	-	-	*+	**+	25
7	-	-	-	-	-	-	34
8	*+	-	-	-	-	**+	56
9	-	*+	*+	-	-	**+	54
10	-	**+	-	-	-	**+	52
11	-	-	-	-	-	*+	49
12	-	-	*+	*+	-	**+	53

# Mean  $\dot{V}O_2 / \dot{V}O_2$  max %

\*\*\* P<0.01

\*\* P<0.05

\* P<0.10

+ indicates significant increase

- indicates significant decrease

**Table 4.8 Summary table of analysis of variance for combined data from the replicated Latin Squares.** The test of significance assumed fixed treatment effects. The analysis demonstrated significant increases in heart rate at rest and at work due to respirator use (treatments). Some day by day (Columns by Squares) variation of heat rate and minute ventilation at work became evident.

Resting Values

Variable	Cols/Sqrs	Rows/Sqrs	Treatments	Sq by Tr
HR (r)	-	-	*+	—
$\dot{V}O_2$ (r)	-	-	-	**+
$\dot{V}CO_2$ (r)	-	-	-	**+
$\dot{V}min$ (r)	-	-	-	*+
R (r)	-	-	-	—
PDB (r)	-	-	***+	*+

Working Values (25-64%  $VO_{2max}$ )

Variable	Cols/Sqrs	Rows/Sqrs	Treatments	Sq by Tr
HR (w)	**+	-	***+	-
$\dot{V}O_2$ (w)	-	-	-	-
$\dot{V}CO_2$ (w)	-	-	*+	-
$\dot{V}min$ (w)	***+	-	-	-
R (w)	-	-	-	—
PDB (w)	-	-	***+	-

\*\*\* P<0.001    \*\* P<0.01    \* P<0.05

+        indicates significant increase  
-        indicates significant decrease

## 4.4 Discussion

The objective of this study was to determine whether wearing an air-purifying respirator imposed an additional physiological strain on an individual. Measures of physiological strain most appropriate to the study were identified earlier in the theoretical framework for the thesis (Chapter 1, section 1.6). Of the stresses identified in the study, only the characteristics of the equipment (inspiratory resistances), subjects clothing and food and beverage intake prior to the study were able to be controlled with some certainty. Environmental conditions (temperature, humidity, air flow) whilst relatively stable were not able to be controlled. External psychosocial stress factors were not evaluated apart from the specific psycho-physiological aspects of respirator use (perceived difficulty breathing). Evidence from this study indicate that the physiological consequences of respirator use are complex and were very dependant on the individuals cardiorespiratory characteristics, as some subjects exhibited physiological strain where others did not.

The complex nature of the interaction between the wearer and the device and the associated physiological responses was further illustrated in Tables 4.2-4.7 where the changes to the variables showed no clear trend and the directions of change were inconsistent between subjects (an increase or decrease in the variable). Several authors, when reviewing the physiological aspects of respirator use have identified this complexity (Raven *et al*, 1979; Louhevaara, 1984; Louhevaara, 1986; Jones, 1991).

### 4.4.1 Physiological Factors

At rest, heart rate, gas exchange and minute ventilation did not appear initially, to be significantly effected by increasing inspiratory resistances imposed by the respirator using a subject by subject analysis, suggesting little detectable physiological strain. This is consistent with the design criteria for most respirators, which require inspiratory pressures of no more than 0.12 kPa at 30 l/min, and at 95 l/min no more than 0.37 kPa. Similarly, expiratory pressures at 85 l/min must not exceed 0.12 kPa

(Australian Standards Association, 1991). The respirator used in this study (Kemira Silner 12) complied with this criteria.

The oxygen cost of breathing has been estimated at less than 5% of the total oxygen consumption (Bartlett *et al*, 1958; Campbell *et al*, 1959; Harden *et al*, 1962). The resting values for respirator use in this study were higher than this estimate (5-11%  $\dot{V}O_2$  max), due to the differing resting criteria used in this study (at rest seated on a cycle ergometer with feet and hands on the ergometer). In a study of resting ventilation by Perez and Tobin (1985), they found that even the use of a mouthpiece or facemask can significantly influence the respiratory variables being measured. Adams *et al*, (1989) found that at a low level of exercise (50W) the use of a mouthpiece induces a lower respiratory frequency at a similar level of alveolar ventilation. However, in response to moderate exercise (75W female, 100W male) the presence of a mouthpiece rather than having little influence on breathing pattern appears to limit the increase in respiratory rate that would normally be expected to occur (Adams *et al*, 1989). However, the results of this study suggest that differences for resting physiological variables when using a mouthpiece or a respirator facemask are minimal.

At moderate and high levels of exercise (25-64%  $\dot{V}O_{2 \text{ max}}$ ) heart rate was unaffected due to respirator use in all but one of the subjects. This finding is consistent with earlier studies (Chaterjee 1969; Epstein *et al*, 1982; Harber *et al*, 1982; Harber *et al*, 1984; Harber *et al*, 1988), that reported minimal, if any, effects on heart rate by the use of a negative pressure respirator. However, observations from this study are inconsistent with those studies that have shown a modest, but significant increase in heart rate during respirator usage in the laboratory (Dressendorfer *et al*, 1977; Raven *et al*, 1979; Louhevaara *et al*, 1984; James *et al*, 1984; Louhevaara *et al*, 1985; Jones 1991). Few explanations have been offered to account for the absence of a cardiac response due to the additional load that the respirator is assumed to impose at moderate levels of submaximal exercise (Raven *et al*, 1979; Louhevaara, 1984; Louhevaara, 1986; Jones, 1991). The data from this study in particular (Table 4.7), clearly illustrates the absence of a response. Reasons for this could be due to the

ability of the relatively young subject group (mean age 24.5 yrs, s.d 4.5 yrs) to tolerate and control additional cardiorespiratory stress more easily than older subjects.

Oxygen consumption and the production of carbon dioxide were significantly ( $P < 0.1$  and  $0.05$ ) affected in only two of the twelve subjects. This supports studies by several authors (Hermansen *et al*, 1972; Harber *et al*, 1984; and Jette *et al*, 1990) who found that  $\dot{V}O_2$  and  $\dot{V}CO_2$  remained almost unchanged up to an exercise level of 75-80% of the maximal oxygen consumption. This implies, as Harber *et al*, (1984) suggested, that even large changes in the work of breathing induced by a respirator would only minimally affect the total oxygen consumption and this effect would be less evident during exercise.

There is general agreement that after reaching a peak at age 15 to 25 yrs,  $\dot{V}O_{2\text{ max}}$  declines by almost 1 percent per year, whether the subject is an athlete who keeps up a high level of activity or an untrained person (Astrand and Rodahl, 1977; Jones *et al*, 1985). In addition age-related structural changes in the respiratory system are associated with reductions in a number of physiological functions; between the ages 20 and 60 vital capacity falls by 19% (Morris *et al*, 1971), maximum airflow by 17%, and the  $FEV_{1.0}$  by 30%; these changes, together with reductions in respiratory muscle strength, lead to a fall in breathing capacity of about 30% (Jones, 1988). The subjects in the present study were relatively young (mean age of 24.5 (4.8) yrs) and did not exhibit these changes.

The minute ventilation remained unchanged during the present series of experiments. This is in contrast to studies which reported that all types of respirators alter the user's natural breathing patterns, including minute ventilation (Sackner *et al*, 1980; Harber *et al*, 1984; Louhevaara, 1984; Jones, 1991). In addition, Harber *et al* (1984), showed that respirators caused increased work by imposing flow resistance and by adding dead space, thus increasing the required total minute ventilation to achieve any particular alveolar ventilation level. Evidence from the present study suggests that the air-flow resistances and dead space volumes of the respirator (Kemira Silner 12) were not significant stresses.

The ventilatory response to an added inspiratory resistance in conscious humans has been extensively studied (refer review by Cherniack *et al*, 1981). The immediate response to the resistance is highly variable. The steady state response is characterised by preservation or increase in tidal volume and inspiratory duration and a decrease in respiratory frequency (Im Hof *et al*, 1986).

The mechanism by which tidal volume is preserved or increased in the steady state is not clear. The respiratory centres of the brain can utilize several mechanisms to compensate for added resistance. These include: increases in inspiratory time and amplitude of inspiratory activity, changes in shape of the rising and declining phases of inspiratory activity, compensation may be accomplished by recruitment of expiratory muscle activity, thereby, lowering end expiratory volume. Any of the can be quite effective in countering an inspiratory resistive load (Im Hof *et al*, 1986).

The detection of added external resistive loads has been studied in healthy subjects, patients with increased airways resistance and patients with neurological abnormalities. The mechanism of resistive load detection however, remains uncertain (Mahutte *et al*, 1983). In their original paper on resistive load detection (Bennett *et al*, 1962) postulated that a load was detected when a disturbance of the pressure-flow relationship occurred and that the rate at which the volume of the chest is increasing is less than expected for the rate at which the pressure developed by the respiratory muscles is increasing. Mahutte *et al*, (1983), suggested that detection of the resistive load essentially occurs because there has been a delay in the expected rate of rise of airflow for the previously preset muscle pressure. Perceived difficulty breathing was a variable that was significantly influenced by respirator use. The mechanism that generated the perception in the present study however, remains uncertain.

When a secondary level of analysis was used on the total pooled data however, conflicting results with the subject by subject analysis were obtained. Heart rate and perceived difficulty breathing were found to be significantly ( $P < 0.05$ ) effected at rest. Explanations for this may include (i) the effect of the artificially increased resistance of the respirator has become a significant strain on users or (ii) that there has been an



increase in resting heart rate due to respirator use. Possible explanations for an increase in heart rate in these circumstances include: increased cardiac demands caused by the increased work of breathing (Craig *et al*, 1970; Louhevaara *et al*, 1985), heat stress (Hodous *et al*, 1989; White *et al*, 1989), increased chemoreceptor or baroreceptor activity caused by the changes in alveolar ventilation and intrathoracic pressure (Hermansen *et al*, 1972) or anxiety related to dyspnea (Harper, 1984).

#### 4.4.2 Possible Sources of Error

A key issue with this experiment is the question of whether the physiological effects recorded are real consequences of respirator use, or whether any non-effect recorded could be a consequence of the accuracy and precision of measurement i.e. effects beyond the detection limits and resolution of the measurement instrument concerned. Accuracy and Precision of Measurements: *Accuracy* is defined as the quality which characterises the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured (Hall, 1977). *Precision* refers to the degree of agreement within a group of measurements. The accuracy of the measurement must be quoted as a tolerance or uncertainty in measurement (Hall, 1977).

In addition to systematic and random measurement errors, other possible sources of error in the experiment include:

- (i) subjects achieving steady state after the exercise regimen whilst wearing a respirator.i.e. going from wearing the respirator with restricted inspiratory valve to using the breathing valve.
- (ii) the training effect of repeated trials whilst wearing the respirator, potentially modifying breathing patterns.
- (iii) the training effect of repeated use of the Perceived difficulty Breathing Scale (PDB Scale) during the course of the trials.
- (iv) the use of the mouth piece of the breathing valve may effect breathing pattern in a different manner than the face mask of the respirator (Perez and Tobin 1985; Adams *et al*, 1989).

#### 4.4.3 Psychological Factors

A number of studies have shown that psychological factors in respirator use also play an important part in altering respiratory patterns (Harber *et al*, 1982; Harber *et al*, 1984; Daubenspeck *et al*, 1983; Killian *et al*, 1981; Morgan, 1983; Harber *et al*, 1991). In their review, Raven Dodson and Davis (1979), cite the early work of Cooper, 1962 who commented:-

"...a man who knows that he will not see his wife and family again unless he wears a respirator will tolerate much more resistance than, say, a miner who is told that if he wears a dust filter on every shift for the next 10 or 20 years, his chances of developing pneumoconiosis will be reduced".

This comment, whilst anecdotal, emphasises the importance of risk perception and the users attitude and beliefs about the hazard they are exposed to. Farid and Lirtzman (1991) observed that "systematic research on how workers perceive and assess job hazards has been virtually non-existent". Similarly, Jacobs and Dopkeen (1990) also commented that while there are numerous studies of objectively determined occupational risk, studies of self-perceived risk are 'sadly lacking'. For many occupational and environmental hazards, the magnitude of the risk is often not apparent and it may be extremely difficult for individuals to assess the severity of the threat and the desirability of taking precautions (Weinstein, 1989). In addition, personal experience is widely believed to have a substantial impact on the recognition of risk (Weinstein, 1989). The evidence suggests that personal experience generally increases feelings of susceptibility and worry, and increases the saliency of the risk, although it may either increase or decrease perceived seriousness, depending on the type of experience or situation (Clark, 1992).

It is only relatively recently that subjective effects of respirator use have been studied in detail (Shimozaki *et al*, 1988; Harber *et al*, 1989; White *et al*, 1989). Visual analogue scales permit the determination of subjective effect without directly supplying specific categorical information (White *et al*, 1989). As a

psychophysiological measure of strain, Perceived Difficulty Breathing (PDB) (a seven point psychophysical category scale), showed significant ( $P < 0.05$ ) increases in all but two subjects working at submaximal levels of external load by analysis of the replicated Latin squares (Table 4.7). This evidence supports studies by Morgan and Raven (1985) and Harber *et al.*, (1991), that wearing respiratory protection does impose a feeling of respiratory distress in individuals exercising at moderate workloads, and manifests itself in a perception of difficulty breathing. The analysis of variance of pooled data showed highly significant ( $P < 0.001$ ) increases in perceived difficulty of breathing both at rest and at work (Table 4.8).

It appears that hyperventilation syndrome plays a role in the production of distress associated with the use of respirators (Morgan, 1983) but, as Morgan and Raven (1985) suggest, it is not clear as to whether or not disturbed respiratory patterns should be viewed as a stimulus, response or a mediating variable in the distress process.

In summary, at the individual locus of analysis (replicated Latin Squares) the series of studies undertaken provided evidence that wearing a respirator at rest ( $5-11\% \dot{V}O_{2\text{ max}}$ ) imposed little detectable physiological strain on an individual. Similarly, at moderate levels of exercise (approx  $25-64\% \dot{V}O_{2\text{ max}}$ ), additional strain (in terms of increases in heart rate, oxygen consumption and carbon dioxide production) were detected in only one out of twelve subjects. The overriding and most common response from all the subjects, was the increased perception of difficulty breathing. This response was also evident when data from the subjects was combined (analysis of variance of pooled data). As a consequence of this secondary analysis, effects from respirator use on heart rate and carbon dioxide production did become significant. However, as the analysis demonstrated significant day to day variation in subject responses at work (significant column effects for heart rate and minute ventilation) the confidence in these findings is reduced.

In conclusion evidence from the present study (using replicated Latin Squares) suggested that:

- (i) Cardiorespiratory strain, as measured by mean heart rate, was not detected at

rest and at work in the majority of subjects wearing respiratory protection that had been modified to artificially increase inspiratory resistance.

- (ii) Changes in oxygen consumption, carbon dioxide production and minute ventilation were not detected in the majority of subjects when wearing respiratory protection at rest or at work.
- (iii) The use of the respirator significantly altered the perception of difficulty breathing in the majority of subjects at rest and at work.

Conclusions from the analysis of variance using pooled data:

- (iv) Significant day to day variations for heart rate and minute ventilation compromised the treatment effects observed.
- (v) The significant increase in carbon dioxide production associated with an unchanged oxygen consumption may have indicated that many of the subjects were hyperventilating as a consequence of respirator use. This was not supported however, by significant changes in respiratory exchange ratios.

## CHAPTER 5

### 5.0 LABORATORY STUDIES ON RATED PERCEIVED EXERTION AND RESPIRATOR USE

#### 5.1 Introduction

The physiological cost of wearing respiratory protective equipment has received considerable attention (see reviews by Raven *et al*, 1979; Louhevaara, 1984 and Jones, 1991). This interest has generated a great deal of physiological data on the body's response to the additional load the respirator imposes (see Raven *et al*, 1979 and Louhevaara, 1984). Recently, further research has been undertaken to determine how this additional load is perceived, in terms of exertion or effort, by the respirator user (Morgan and Raven, 1985; Shimosaki *et al*, 1988; Wilson *et al* 1989; Jette *et al*, 1990). For over thirty years, research on perceived exertion has received considerable attention (Borg, 1962; Borg and Dahlstrom, 1962; Borg, 1970; Borg and Linderholm, 1970; Borg and Noble, 1974; Gamberale, 1972; Grimby *et al*, 1972; Morgan, 1973; Borg *et al*, 1980; Flieshman *et al*, 1984; Ljunggren 1986). These studies supported the view that the perception of exertion is a reliable indicator of the degree of physiological strain and also is an indirect indicator of physical work activity (Ljunggren, 1986). Early work by Borg (1962) showed a linear relationship between perceived exertion and certain critical physiological variables (e.g. heart rate). He concluded that perceived exertion is an important measure of an individuals strain and can be used to complement or as an alternative to measured physiological variables (Borg and Dahlstrom, 1962).

Borg (1962) developed a simple category rating scale, the RPE scale (rating scale of perceived exertion, see Fig. 5.1). This has been extensively used since that time within both the clinical and sports medicine fields. The effectiveness of the use of the scale with individuals in the industrial environment has only recently become evident (refer reviews by Ljunggren, 1986; Jette *et al*, 1990). The application of the scale in industrial situations has become important for 'work physiology' where

perceived estimations of workload are required for certain work tasks.

The values of the RPE Scale were chosen to be as close as possible to one tenth of the corresponding heart rate. High correlations have been obtained between ratings and heart rate in several studies (Borg, 1962; Borg and Linderholm, 1970; Skinner *et al.*, 1970).

**Fig. 5.1 Values of Rated Perceived Exertion (RPE) and their verbal descriptions.**

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

Early studies using the Borg scale were mainly concerned with its reliability and validity for different types of physical work. At an international symposium in Sweden in 1977, experimental evidence was presented in support of a basic two-factor model posed by Ekblom and Goldbarg (1971), which followed up suggestions from Borg's original work. The two-factor model involves the interaction of two primary influences in the perception of exertion. Firstly, a local factor i.e. feelings of strain in the working muscles and/or joints and secondly, a central factor, i.e. sensations or feelings involving the cardio-respiratory system.

In his review of the literature, Pandolf (1978), cites over 30 references concerning local and/or central factor involvement in ratings of exertion during physical work. On examination of his review, there appears to be enough experimental evidence to support the existence of the two factor model (local and central), which act as cognitive cues in determining rated perceived exertion. The dominance of either local or central factors in the subjective estimate of exertion appears, in part, to be related to the amount of active muscle mass employed by the particular type of physical work (Pandolf, 1978). Subsequent reviews (Mihevic, 1981; Pandolf, 1982; Pandolf, 1983; Goslin and Rorke, 1986) have provided strong support for the influence of local factors in fatigue, and cite increasing evidence that central factors do not play as important a role in the perception of exertion as was originally thought (Ekblom and Goldbarg, 1971; Gamberale, 1972; Borg and Noble, 1974; Pandolf, 1982). Also of importance to the results of this study, Ljunggren (1986) suggested that the 'total' estimation of perceived exertion ought to include an integration of several different cues, such as feelings of how heavy an individual is pedalling on a cycle ergometer i.e. the perceived work resistance (Borg, 1962; Pandolf, 1982).

The study by Goslin and Rorke, (1986), examined the effects of backpack load carriage on rated perceived exertion (RPE). With the exception of breathing frequency (which did not change), ventilatory, cardio-respiratory and RPE responses increased linearly with increases in the load carried and relative speed. When the increment in RPE over its maximum range was compared to the relative change in heart rate and oxygen consumption, it was observed that as soon as added load was carried the perception of exertion increased almost twice as much as did the cardio-respiratory measures when compared with non-loaded walks. This supports the contention that 'local' factors, if accentuated by load carriage, can dominate the overall perception of exertion. Shimozaki *et al*, (1988), provided evidence that subjective responses to a variety of respiratory loads can be measured by the use of visual analogue scales. Two scales were consequently developed from this study: EXERT (perceived limitation of exercise duration) and DISC (perceived discomfort). The study found a linear relationship between inspiratory resistance and subjective response.

Wilson *et al*, (1989) investigated the changes in physiological and perceptual variables during exhausting endurance work with and without an air-supplied, full-face piece, pressure demand respirator. Subjects walked on a treadmill to exhaustion at a rate calculated to elicit 70% maximal oxygen consumption. The authors concluded that respirator wear during endurance exercise to exhaustion resulted in a significant increase in the physiological effort of breathing to overcome the added resistance. In addition, they observed that the increased effort of breathing increased the perception of exercise intensity and resulted in an earlier termination of exercise. They found that some, but not all, individuals experienced respiratory and psychological distress as evidenced by the steep increase in RPE and difficulty breathing scales when wearing the respirator. However, overall, no significant differences in heart rate, frequency of breathing, rated perceived exertion and breathing distress were observed in the subject group.

Jette *et al*, (1990), found that maximal aerobic power and performance time, as determined by progressive treadmill tests, were not influenced by the resistance imposed using a military type chemical and biological respirator loaded with three different types of purifying canisters. Results indicated that maximal oxygen consumption, mean maximal respiratory exchange ratio, mean maximal heart rate, mean rated perceived exertion (RPE) and blood lactate levels were not significantly influenced by breathing through the mask and canisters in comparison to a laboratory breathing valve. Mean maximal pulmonary ventilations, however, were significantly lowered from 133 l/min using the breathing valve to 102, 103, 109 l/min using the mask and three different types of canisters. This is not inconsistent, as ventilation in normal subjects at maximal exercise only reaches 60 to 75 per cent of the maximum voluntary ventilation (MVV), indicating that reserve is still present in the ventilatory capacity (Jones, 1988).

Rating scales for perceived effort have been well validated and may now be made an integral part of all exercise tests (Jones, 1988). Most work physiologists regard effort in terms of energy expenditure and it is usually expressed as a respiratory, metabolic or cardiovascular variable (Gamberale, 1972; Astrand and Rodahl, 1977; Louhevaara



*et al*, 1984). In physically demanding work, an individuals' physical capability and his/her psychological perceptions interact at all levels of task performance (Borg, 1962; Borg and Noble, 1974; Fleishman *et al*, 1984). According to Fleishman *et al*, (1984), the physical and psychological factors in work performance operate reciprocally in cueing muscular and cardiovascular effort in relation to feelings of workload, exertion and fatigue.

Perceptual variables have been suggested as being important factors in respirator tolerance by a number of authors (Louhevaara, 1986; Shimozaiki *et al*, 1988; Jette *et al*, 1990; Harber *et al*, 1991) and, as they were also prevalent amongst the reasons for respirator non-use in the usage survey (Chapter 2), this leads to the proposition that factors such as perceived exertion when wearing a respirator play an important part in respirator non-use. The objective of this part of the study therefore, was to examine the effect the wearing of a respirator has on mean heart rate and rated perceived exertion (RPE) at varying levels of external work and, in addition, to determine whether these physiological and psychological variables are linked.

## 5.2 Materials, Method and Equipment

### 5.2.1 Subjects

A series of experiments were carried out on seven adult volunteers, working at randomised workloads on a cycle ergometer. The subjects were informed about the experiment's objectives and procedures, and signed a document to that effect in accordance with the protocol approved by the Massey University Human Ethics Committee.

### 5.2.2 Experimental Design and Measurements

Each subject performed duplicate tests; one test with and one test without wearing a respirator of known physical characteristics (Kemira Silner 12, 0.23 kPa at 85 l/min inspiratory resistance, 0.2 kPa at 85 l/min expiratory resistance; 190 ml dead space volume; 355 gm dry weight). The respirator had cartridges specific for organic vapours and gases. Each test consisted of four, five minute periods of work on the

cycle ergometer. The work levels were undertaken in a randomised order at 25, 50, 75 and 100W with a pedalling frequency of 60 per minute. Each test had a different randomisation sequence from its duplicate.

Subjects cycled on a standard Monark cycle ergometer (Ergomedic 818E), calibrated using a 5kg dry weight. Heart rate was measured using a Sport Tester PE-3000 heart rate monitor, calibrated against a standard 3 lead ECG amplifier and cardiac ratemeter (Jrak BioSignals Ltd., Windsor, Vic., Australia), and accurate to within  $\pm 1.0\%$ . The heart rate data was monitored continuously and mean heart rate was recorded at one minute intervals throughout the test. Variables measured were heart rate (HR), and the rated perceived exertion (RPE), using the RPE scale as developed by Borg (1962) (shown in Figure 5.1.). When using the RPE Scale the subjects were asked to state how hard the work 'feels'. The assessments were made by asking each subject to point at the number which best described his/ her perception of effort. The protocol for the implementation of the Borg scale requires that in the instructions preceding the rating, no mention is made to any particular or local feeling of exertion. The intention is for the individual to concentrate on general feelings of exertion as opposed to specific instances of muscle fatigue or discomfort. The assessment of RPE was undertaken during the fourth minute of the five minute exercise period.

### 5.2.3 Environmental Variables

General environmental conditions, including ambient air temperature ( $T_d$  and  $T_{wb}$ ) and relative humidity were recorded using a standard whirling hygrometer (Cassella, England). In addition, the type of clothing worn by the subjects and the onset of sweating and facial colouration during the experiment were also noted.

### 5.2.4 Statistical Analysis

Data was recorded on a proforma data sheet and statistical analysis was undertaken using a paired t-test and Pearson correlation coefficient (Minitab Inc., Release 8.2, 1991). P-values of 0.001, 0.01 and 0.05 were used to determine statistical significance.

### 5.3 Results

The subjects were seven healthy volunteers (two females and five males) who had worn a respirator at some time before. Table 5.1 shows the physical characteristics of the subjects in terms of average age, height and weight for both male and female subjects. The ambient room air temperature ranged from 17-20 °C  $T_a$  and 13-16 °C  $T_{wb}$ .

**Table 5.1 Physical characteristics of the subjects including mean and standard deviations for age, height and weight.**

Subject*	Age(yrs)	Height(cm)	Mass(kg)
Af	23	160	61.0
Bf	20	167	70.6
Mean	21.5	163.5	65.8
s.d.	2.1	4.9	6.8
Cm	24	183	72.6
Dm	26	178	75.7
Em	22	176	95.2
Fm	32	193	101.0
Gm	27	187	85.0
Mean	24.86	177.7	80.14
s.d.	3.98	11.4	14.6

\* f, female; m, male

Table 5.2 shows the mean heart rate (beats/ min) for the seven subjects at the four differing levels of external work (25W, 50W, 75W, 100W). Mean heart rates and standard deviations ( ) are given, and the level of significance.

**Table 5.2** Mean heart rates for the seven subjects at differing levels of work, with and without wearing a respirator. (mean  $\pm$  sd; work level 1=25W, 2=50W, 3=75W, 4=100W).

Subject	Work Level							
	1		2		3		4	
	Without	With	Without	With	Without	With	Without	With
A	126(4.2) *	133.4(1.8)	134.2(2)	125.4(3.3) (*)	143.6(8.0)	131.6(5.5) (*)	148.8(11.7) NS	157.2(5)
B	99.6(1.9) **	103.2(0.8)	98.6(3.2)	103.6(1.8) *	112.8(1.9)	111.4(2.4) NS	123.4(5.5) NS	129.6(5.7)
C	116.6(3.5) (***)	102.4(1.5)	116.0(1.8)	108.0(2.5) (***)	126.2(2.0)	114.6(2.3) (***)	134.4(6.7) *	144.6(5.7)
D	101.2(2.7) ***	111.2(3.4)	101.8(1.6)	112.6(2.4) ***	108.6(1.3)	117.8(2.6) ***	112.0(4.5) **	121.0(2.1)
E	119.4(0.9) (***)	101.8(2.4)	131.8(2.7)	119.8(4.4) (*)	132.8(3.0)	130.2(3.1) NS	148.4(4.8) (**)	128.4(10)
F	103.6(1.3) (**)	96.4(1.9)	104.4(2.2)	98.4(1.3) (*)	106.6(3.9)	108.0(1.4) NS	114.6(1.5) NS	110.6(3.5)
G	97.4(0.9) **	103.6(2.8)	102.6(2.7)	111.0(4.0) **	112.0(2.9)	123.6(3.0) ***	123.2(2.6) ***	134(1.9)

\* P<0.05 \*\* P<0.01 \*\*\* P<0.001

( ) significant lowering of heart rate.

Of the seven subjects, four showed significant ( $P<0.05$ ) increases in mean heart rates when wearing the respirator at work level 1 (subjects A,B,D,G); three subjects showed significant ( $P<0.05$ ) increases in mean heart rates when wearing the respirator at work level 2 (B,D,G); two subjects showed significant ( $P<0.001$ ) increases in mean heart rates when wearing the respirator at work level 3 (D,G) and three subjects showed significant ( $P<0.05$ ) increases in mean heart rates when wearing the respirator at work level 4 (C,D,G). Four subjects (A,C,E,F) showed significant decreases in heart rate as a result of respirator use at light to moderate workloads. These findings are consistent with earlier studies (reviews by Raven *et al*, 1979; Louhevaara, 1984; Jones 1991) that showed that air purifying respirator use either increased, decreased or had no measurable effect on mean heart rate.

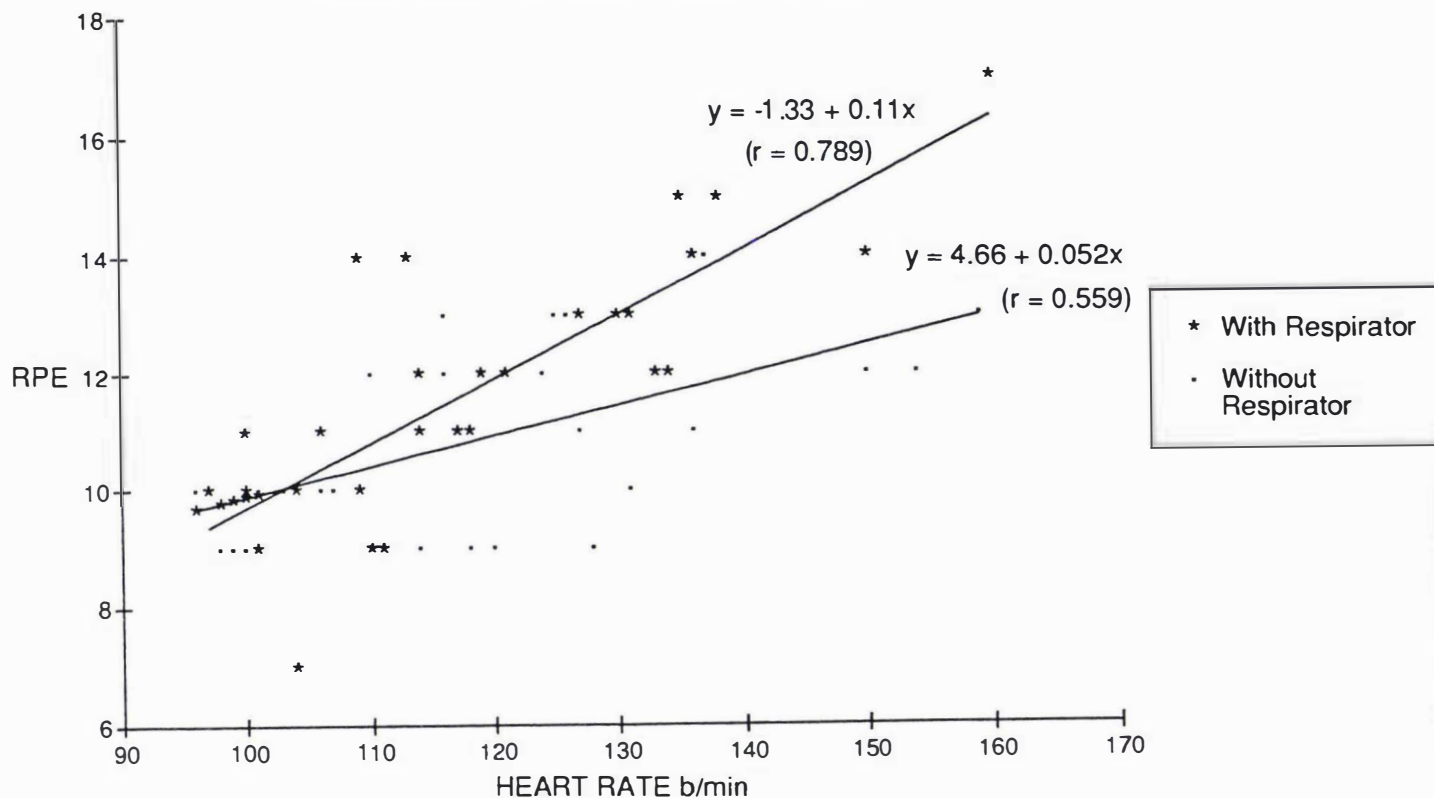
Table 5.3 shows the mean rated perceived exertion (RPE) for the seven subjects at differing work levels, with and without wearing a respirator. Significant differences were seen particularly at higher work levels. Overall, the mean values in rated perceived exertion, with and without the respirator was 11.0(1.6) and 11.9(2.2) respectively ( $P = 0.059$ ).

**Table 5.3 Mean rated perceived exertion (RPE) at differing work levels, with and without wearing a respirator.** (Mean  $\pm$ s.d.) Work Level 1=25W 2=50W 3=75W 4=100W.

Work Level	Without Respirator	With Respirator	P
1	9.75 (0.86)	10.0 (1.4)	NS
2	9.87 (0.83)	10.6 (1.5)	*
3	11.62 (1.06)	12.87 (1.35)	**
4	13 (0.75)	14.25 (1.5)	**

NS    Not Significant  
\*      $P<0.05$   
\*\*     $P<0.01$   
\*\*\*    $P<0.001$

## RPE v Heart Rate With and Without Respirator Use



**Fig. 5.2** Regression lines, formulae and correlation coefficients for the experimental trials with and without wearing respiratory protection.

These results are also consistent with earlier research (Wilson *et al*, 1989, Jette *et al*, 1990) that demonstrated a detectable increase in perceived exertion as a result of respirator use at moderate levels of work (work levels 2, 3,4). In addition, at very low levels of external work (work level 1) the perception of increased exertion due to the wearing of a respirator in this study was not significant ( $P>0.05$ ).

The relationship between Rated Perceived Exertion and heart rate for both experimental trials, with and without respirator use, was examined using the Pearson correlation coefficient. Figure 5.2 shows the regression lines and formulae for the two trials. The figure indicates, that when wearing the respirator a good correlation between RPE and heart rate was obtained ( $r=0.789$ ). When the respirator was not worn, the correlation between RPE and heart rate was only moderate ( $r=0.559$ ).

An important issue in the methodology was the inclusion of female subjects in the experimental protocol and the determination of gender differences. The results indicate that there were no significant difference in values for rated perceived exertion (RPE) between the male and female subjects ( $P=0.657$  with respirator,  $P=0.26$  without the respirator). However, a significant difference in mean heart rate between female and male subjects was established (female mean HR with respirator 124.4(17.4), male mean HR with respirator 114.9(12.8)  $P<0.01$ ); female mean HR without respirator 123.5(18.6), male mean HR without respirator 115.7(13.6)  $P<0.05$ )).

The results of this study indicate that mean heart rates, varied considerably as a result of wearing a respirator, of known weight, external dead space and air flow resistance (Table 5.2) at a predetermined external workload. Three subjects showed a predominant lowering in mean heart rates, whilst three subjects had resultant increases in mean heart rates. One subject showed variations either way. Overall there appears no clear indication of the effect of wearing a respirator in this study, as measured by changes in mean heart rate.

Ambient air temperatures and observations of subjects physical condition, including sweating and skin colouration are shown in Figure 5.3. In addition comments from the subjects on their subjective perceptions during the experiment were recorded and are shown in Table 5.4.

**Fig. 5.3 Environmental variables and observations of sweating and skin colouration in the experimental trials with and without wearing the respirator (%RH = relative humidity).**

Subject	Respirator Condition	Td °C	Twb °C	%RH	Sweating	Skin Colour
A	With	18.5	15.1	68	Forehead	Reddening
A	Without	18.0	14.5	72	Cheeks	Reddening
B	With	18.3	16.2	78	Face	Reddening
B	Without	17.2	14.1	82	-	-
C	With	19.0	15.4	62	Face	Reddening
C	Without	19.1	15.5	64	Face	-
D	With	18.3	15.0	70	Face	Reddening
D	Without	19.0	16.3	66	Face	-
E	With	17.5	13.7	72	Forehead	-
E	Without	19.0	15.1	62	-	-
F	With	17.6	14.2	74	Face	Reddening
F	Without	17.1	15.0	88	Face	-
G	With	18.2	15.3	72	Face	Reddening
G	Without	20.0	16.4	57	-	-



**Table 5.4 Comments reported by the seven subjects of experimental trials with and without wearing the respirator.**

<b>With Respirator</b>	<b>Without Respirator</b>
You could smell the respirator	Able to breath through nose and mouth
Feel a drying sensation	Not as hot
Pushed skin down	Perspiring a lot less
Uncomfortable, Hot	Generally O.K. no problems
The respirator slid on the face	The workload was noticeable
You could feel your perspiration	Felt hot all over
Made cycling hard	Legs hurt at the beginning, muscles got tired
Sweat went into eyes	Quite relaxed
Felt head getting hot	
Not bad	
Got sticky when work level increased	
Noticed breathing, number of breaths	
Wanted to rip it off	
A little problem breathing	
Didn't affect breathing	
Weight on nose a problem	
You feel you have to take a deep breath	

When subjects wore the respirator, the most frequently reported perceptions included adverse thermal sensations, discomfort due to perspiration on and around the face and the weight of the device. Other comments referred to by the subjects included the odour (smell) of the respirator, the pressure exerted on the face by the mask and an awareness of the individuals breathing frequency.

## 5.4 Discussion

The aim of this study was to examine the effect respirator use has on heart rate and rated perceived exertion of subjects at varying levels of external work and in addition, to determine whether these variables are linked.

Female subjects were included in this study in an attempt to gain information on potential gender differences. Although female mean heart rates at work were found to be significantly higher than mean heart rates of the male subjects, the values were found to be consistent with values determined by Astrand and Rodahl (1977). The heart rate data for both male and female subjects were pooled for group comparisons, specifically to determine differences of respirator use and non-use. As a consequence, the higher female heart rates would tend to elevate the group mean heart rates with and without respirator use.

The two female and five male subjects provided heart rate and RPE data that were comparable with, although substantially lower than, the study by Wilson *et al*, (1989). This is consistent with the maximal exercise protocol used in his study (mean maximal heart rate without respirator 185 (2) range 150-201, with respirator 184(2) range 142-200). Although the device used in the Wilson *et al*, (1989) study was an air-supplied device as opposed to an air-purifying respirator used in the present study, the results show comparable relative increases in RPE values. This is significant because of the light to moderate exercise regimen undertaken by subjects in this study (25 - 100 W at 60 revs/min on the cycle ergometer for 20 mins) compared with the extreme (exercise to exhaustion) protocol of the Wilson *et al*, (1989) study. Whilst it is of interest to determine the physiological responses of respirator use under these extreme conditions, the results of the present study tend to provide information on conditions more appropriate to routine industrial work situations, where levels of work very rarely approach maximal physiological limits .i.e. maximum heart rate, maximum oxygen consumption.

The results of the present study however, differ from those of the study undertaken by Jette *et al*, (1990), who found no significant differences in RPE were observed between various respirator assemblies and a breathing valve when exercising to exhaustion on a treadmill. This may be due to the effect the breathing valve may have on patterns of breathing (Adams *et al*, 1989) and consequently on perceptions of effort. A breathing valve was deliberately not used in the present study.

It has become increasingly apparent that perception of exertion is affected by a complex interaction of many influences. The data collected on heart rates for both male and female subjects in the present study does not show clear patterns of cardiorespiratory strain in all subjects. These findings are also consistent with laboratory studies on the physiological cost of respirator use (Chapter 4). However, in both studies, psychophysical perceptions were consistently elevated (perceived difficulty breathing (PDB) in Chapter 4 and rated perceived exertion (RPE) in the current study). The correlations between RPE and heart rate also tend to confirm the heightened perceptual responses when respirators were worn. The higher correlation coefficient obtained when the respirator was worn ( $r=0.789$ ), tends to indicate the subjects were more precise in their subjective estimation of effort as it relates to heart rate when wearing a respirator.

The perception of exertion experienced by the subjects in the present study, increased progressively with each level of work and, more significantly, when the respirator was worn by the subject (Table 5.3). No significant effect of the respirator on perceived exertion was measured at very low levels of external work (25W on cycle ergometer for 5 mins). However, as work rate increased, the relative magnitude of the differences in the ratings of exertion, with and without the respirator, correspondingly increased i.e. difference in mean RPE values work level 1 = 0.25, level 2 = 0.75, level 3 = 1.25, level 4 = 1.25 (Table 5.3). These observations are in agreement with the findings of Wilson *et al*, (1989) who identified similar differences in the magnitude of the change in RPE values with and without a respirator. As the overall mean RPE values were significant at the 6% level ( $P=0.059$ ) supports the view that exertion or effort when wearing a respirator is a complex phenomenon that cannot be explained

by a single physiological parameter.

It was also evident (Fig. 5.3) from the behavioural cues observed of the subjects in the present study (sweating, heavy breathing, bodily movements, change in facial colour) that in some cases the levels of exertion did become excessive. Facial sweating and reddening of the face became more apparent when the respirator was worn. The comments of the subjects (Table 5.4) also confirmed these responses.

The other perceptual cues of particular interest were an awareness of the odour of the respirator, the pressure exerted by the respirator mask on the face and the individuals pattern of breathing. The part the olfactory sense plays in perceptions of discomfort during respirator use has not been reported in the literature to date. Of importance in the production of the odour would be the constituent of the mask (rubber or silicone) the temperature and humidity of the mask micro-environment, the perspiration inside the mask and possibly the subject's breath odour.

The pressure exerted on the face by the respirator has been cited as a potential source of discomfort for respirator users in earlier studies (see reviews by Raven *et al*, 1979 and Louhevaara, 1984; Morgan and Raven, 1985). The strapping mechanism and the size and configuration of the face mask itself would likely be important factors in discomfort due to mask pressure. Whilst this factor is important, it cannot be totally overcome as the complete and efficient seal on the face by the respirator is an essential requirement in industrial situations where individuals are exposed to toxic hazards.

An awareness of breathing by an individual wearing a respirator is a good indicator of the subject's heightened perceptual response. Although many studies have identified changes in patterns of breathing during respirator use (Hermansen *et al*, 1972; Love *et al*, 1977; Raven *et al*, 1979; Harber *et al*, 1984; Louhevaara, 1984; Louhevaara *et al*, 1984; Jones, 1991), little is found in the literature concerning the respirator user's awareness of their own breathing pattern. This factor is particularly relevant to a number of studies in this thesis. Comments from respirator users

(Chapter 2) and volunteer subjects (Chapter 4) indicated that awareness of breathing pattern was an issue in respirator tolerance. This sensation may be heightened by the pressure fluctuations caused by expiratory valve opening and closing at end points of the reciprocating flow cycle identified in Chapter 3.

In conclusion, evidence from the present study suggests that:

- (i) No clear indication of cardiorespiratory strain (mean heart rate) was evident when the subjects wore respiratory protection. The devices increased, decreased or had no measurable effect on mean heart rates (Table 5.2).
- (ii) The rated perceived exertion associated with wearing a respirator may increase significantly ( $P < 0.05$ ) at light to moderate exercise levels (50, 75, 100W on cycle ergometer for 5 mins) (Table 5.3).
- (iii) The correlations between RPE and heart rate were high ( $r = 0.789$ ) when the respirator was worn and moderate ( $r = 0.559$ ) when not worn, indicating a possible perceptual elevation during respirator use (Fig. 5.2).
- (iv) In addition to thermal sensations, other subjective factors such as odours, facial pressure and an awareness of breathing pattern may play a part in feelings discomfort with respirator use. Most subjects indicated discomfort while wearing the respirator, and that breathing required more effort (Table 5.4).

## CHAPTER 6

### 6.0 LABORATORY STUDIES ON THE EFFECT OF RESPIRATOR USE ON SKIN TEMPERATURE

#### 6.1 Introduction

One of the most common reasons for not wearing or removing air-purifying respirators has been found to be thermal discomfort (see Chapter 2 section 2.4, also refer Martin and Goldman, 1972; Hodous *et al*, 1989; Laird *et al*, 1993). Thermal stress and discomfort have been the primary factor in the non-use of respirators in numerous working situations, e.g mine rescue, fire fighting and atomic reactor repair (Raven *et al*, 1979). Early work by Lind (1955) noted that subjects resting in cool conditions and breathing hot, moist air had no discomfort until the wet-bulb temperature of inspired air reached 54.5 to 63 °C and found breathing just tolerable at wet-bulb temperatures of 59 to 65°C. However, wet-bulb temperatures that produced similar sensations were reduced to 51.5 and 54.5°C respectively during moderate levels of exercise.

Lind's experiments indicated that if the inspired air temperature became greater than body temperature (rectal temperature), the heat loss via the lungs was eliminated and heat gain occurred. Consequently, the tolerance time of a person wearing a respirator was significantly reduced when the inspired air temperature was above body temperature (Raven *et al*, 1979). In normal conditions this situation is likely not to occur. However, in hot humid work environments the transpulmonary heat gain, as suggested by Lind (1955), could occur. Emerson *et al*, (1967), demonstrated that certain surgical masks caused as much as a 5°C rise in facial temperature along with a 16 % increase in the relative humidity of inspired air. Such conditions have been related to subjective fatigue and an increased number of mental errors (Raven *et al*, 1979).

Atterbom and Mossman (1978), suggested that the best indicator of thermal stress was heart rate. Nielsen, Gwosdow, Berglund and DuBois (1987), found that heat stress to workers using respirators was important, because acceptance of a respirator appeared to be limited by the combination of high skin temperature and skin wettedness, both locally in the mask and for the entire body.

The warm 'microclimate' of the inside of the face mask may also produce unpleasant sensations, only partially explained by reduced respiratory heat loss (Nielsen *et al*, 1987a, 1987b). Hodous *et al*, (1989) reported that the most 'bothersome' aspect of wearing respiratory protective devices by his subjects was the excessive temperature inside the devices. Studies have attempted to quantify subjective assessments of discomfort associated with a range of ambient air and skin temperatures whilst wearing respirators (Nielsen *et al*, 1987a, 1987b; White *et al*, 1989; Gwosdow *et al*, 1989; DuBois *et al*, 1990). These studies indicated that facial skin temperatures in excess of 34.5 °C inside the mask are perceived as 'warm', 'uncomfortable' and 'sweaty' by the wearer. Gwosdow *et al*, (1989) found that respirator discomfort was primarily affected by the temperature and humidity conditions inside the respirator and that thermal sensations were perceived 'in accord' with lip skin temperature. At lip skin temperatures between 32.5 °C and 34.5 °C, the respirator was acceptable to all subjects. The thermal conditions were subjectively rated as 'comfortable', with neutral thermal sensation, minimal sweating and little sense of skin wettedness. As the lip temperature rose above 34.5 °C, respirator acceptability decreased markedly. The reduced acceptability was reflected by changes in subjective responses. The respirator environment felt 'warmer' and 'uncomfortable'.

Discomfort resulting from wearing the respirator has been attributed by Martin and Goldman (1972) and by Martin and Callaway (1974) to be the decrease in thermal exchange between the respirator wearer and his/her environment. Despite discomfort fireman, miners and rescue workers typically tolerate hot, humid air inside respirators for the time required to complete their jobs because the health risk of doing otherwise is clear (Gwosdow *et al*, 1989).

Perceptions of the whole body thermal environment generally are considered to be determined by the combined effect of internal body and local skin temperatures. By integrating this information in the central nervous system, an individual is able to assess thermal sensation, discomfort and other subjective responses (Gagge *et al*, 1967; Gwosdow *et al*, 1989).

It has been suggested that the degree of skin wettedness becomes the primary determinant of discomfort, while mean skin temperature is only important when the skin wettedness has reached its maximum (Gagge, Stolwijk and Nishi, 1969; Gagge, Stolwijk and Saltin, 1969; Gwosdow *et al*, 1989). In a cold environment, thermal discomfort is primarily a function of mean skin temperature (Winslow *et al*, 1937; Gagge, Stolwijk and Hardy, 1967) although differing levels of metabolic rate will change the mean skin temperatures that is considered comfortable (Fanger, 1970).

Jones (1991) examined the use of disposable respirators and found an average increase of facial skin temperature (lip) of 7.5 °C whilst using a respirator. He proposed that an increase in heart rate may be a good indicator of thermal stress and that an increase in breathing rate may represent an attempt to dissipate heat. Even in comfortable ambient temperatures, increased air temperature and humidity under the respirator may limit an individuals acceptance of the respirator (Jones,1991).

Taking into account the fact that much of the literature suggests that facial skin temperature is an important factor in respirator acceptability and also that thermal conditions were major reasons for respirator non-use in the respirator survey (Chapter 2), the aim of the current experiment was to examine the affect of wearing a moderate to high resistance air-purifying respirator on heart rate and local skin temperature using volunteers working at submaximal levels of external work.



## 6.2 Materials, Method and Equipment

### 6.2.1 Subjects

A series of experiments were carried out on five adult volunteers, working at a constant workload on a cycle ergometer. The subjects were informed about the experiment's objectives and procedures and signed a document to that effect in accordance with the protocol approved by the Massey University Human Ethics Committee. This identified the potential risks in undertaking the submaximal exercise regimen, the procedures to minimise risk of harm to the subject, the support and facilities available should an emergency occur, the right of the subject to discontinue the experiment should they so wish and the confidentiality and anonymity of the physiological measurements.

### 6.2.2 Experimental Design

The experimental procedure was as follows: each subject performed a series of tests, which consisted of 30 minute intervals of work on a cycle ergometer, 15 minutes wearing a respirator and 15 minutes without a respirator (Test 1). Each subject then performed a duplicate test, at the same time of day to the previous test, separated by at least 24 hrs (Test 2). The order of the respirator use was reversed for the duplicate test i.e. 15 minutes without the respirator, then 15 minutes wearing the respirator (the reverse of the first experiment). The rate of work was kept constant throughout the two tests at 50W external load, with a pedalling frequency of 60 per minute.

### 6.2.3 Measurements and Techniques

A standard Monark cycle ergometer was used (Ergomedic 818E) to generate the work load and a Sport Tester PE-3000 (Polar Electro, Finland) was used to measure heart rate. The heart rate data were monitored continuously and mean heart rate was recorded at one minute intervals throughout the test using the Sport Tester PE-3000. The variables measured were heart rate (HR) and skin surface temperature on the upper lip and on the cheek near the ear lobe. Skin temperature was measured using two NTC (negative temperature coefficient) thermocouples attached to 15mm diameter aluminium discs and positioned (i) on the upper left lip approximately 2 cm anterior

to the midpoint between the base of the nose and the upper lip and (ii) on the left cheek (4 cm anterior to the exterior auditory meatus). Temperature readings for the two thermocouples were displayed on a digital temperature meter. A switch selected the channel corresponding to the appropriate thermocouple. The thermocouples were calibrated by using a water immersion technique. This involved measurement of a range of temperatures from 21.0-35.0 °C using a water bath and mercury in glass thermometer. The two thermistors were immersed in the warm bath and positioned as close as practicable to each other at the site of measurement. The water was allowed to cool and recordings of actual (mercury thermometer) and measured (thermistor) temperatures were taken. The accuracy of the thermistors were found to be within  $\pm 0.5$  °C (Thermistor 1) and  $\pm 0.6$  °C (Thermistor 2). The same thermocouples were used in all tests and temperature was monitored continuously and recorded at the end of every minute of work throughout each 30 minute experimental protocol.

#### 6.2.4 Environmental Variables

General environmental conditions, including ambient air temperature ( $T_a$  and  $T_{wb}$ ) and relative humidity of the test room was also recorded using a standard whirling hygrometer (Cassella, England). The type of clothing worn by the subjects and the onset of sweating, heavy breathing, changes in facial colouration during the experiment was recorded. In addition, subjects were asked if they had any other comments to make about the experiment and how they felt.

#### 6.2.5 Statistical Analysis

The data were analyzed using descriptive statistics (Minitab Inc, Release 8.2, 1991), a paired-t test analysis and Pearson correlation coefficient was used to compare measurements on the subjects with and without the respirator. Standard P values of 0.05, 0.01 and 0.001 were used to determine statistical significance.

### 6.3 Results

#### 6.3.1 Subjects

The subjects (2 female, 3 male) were healthy volunteers who had used, albeit infrequently, respiratory protection before. Table 6.1 shows the physical characteristics of the subjects. Although the study group of subjects was small, the average age, height and weight of the five subjects are also shown. The female subjects were younger and lighter than the male subjects. The mean heights of the subjects were similar. The ambient room air temperature ranged from 18-21 °C  $T_d$  and 14-16 °C  $T_{wb}$  with relative humidities (%RH) between 47 -67%.

**Table 6.1 Physical characteristics of the subjects including age, height and weight.**

SUBJECT*	AGE(yrs)	HEIGHT(cm)	MASS(kg)
Af	31	184	68.6
Bf	32	172	65.8
Mean (sd)	31.5(0.71)	178.0(8.5)	67.2(2.0)
Cm	38	182	84.6
Dm	41	182	81.4
Em	47	176	66.4
Mean(s.d.)	42.0(4.6)	180.0(3.5)	72.5(9.7)

\* m, male; f, female

6.3.2 Mean Heart Rates

Table 6.2. shows the mean heart rate data for the five subjects with and without wearing a respirator. There was no overall significant difference between heart rates at this work level with and without the respirator.

**Table 6.2 Mean heart rate data for the five subjects with and without wearing a respirator. (Mean±s.d.)**

SUBJECT+	TEST 1			TEST 2		
	WITHOUT	WITH	P	WITHOUT	WITH	P
Af	110.36(2.98)	108.62(4.9)	NS	104.87(4.3)	107.3(2.4)	*
Bf	110.67(2.4)	111.09(2.3)	NS	110.3(1.5)	110.5(1.9)	NS
Cm	102.18(4.3)	109.29(3.4)	***	84.77(2.6)	85.71(2.9)	NS
Dm	140.25(2.0)	136.75(1.7)	(***)	111.61(3.2)	116.6(1.4)	***
Em	111.2(3.1)	116.7(5.1)	***	110.7(5.3)	117.5(2.3)	***
Mean	108.9(13.4)	110.94(12.7)	NS	105.6(1.4)	106.2(1.3)	NS

\* P<0.05    \*\* P<0.01    \*\*\* P<0.001    ( ) indicates decrease in heart rate  
+ m, male; f, female

Subject A had a significant (P<0.05) increase in heart rate due to respirator use in the second test (Test 2). Subject B showed no significant variations in both tests. Wearing the respirator had a significant (P<0.001) effect on the mean heart rates for Subjects C, D and E (Test 1 for subject C; Test 2 for subject D and Tests 1 and 2 for subject E). Subject D had an anomalous decrease in mean heart rate in the first test (Test 1). The very high mean working heart rate for subject D (140.25(2.0) b/min) was anomalous and the subject indicated he was stressed before the test began. This was confirmed on completion of the second test where the mean working heart rates were considerably lower (110-116 b/min).

### 6.3.3 Skin Temperatures

Table 6.3 shows the mean facial skin temperature (cheek) with and without wearing a respirator. There was an overall significant ( $P < 0.001$ ) mean increase in cheek temperature with the respirator on of  $0.7^{\circ}\text{C}$ .

**Table 6.3 Mean facial skin temperatures (cheek) with and without wearing a respirator. Mean (s.d.)**

SUBJECT+	TEST 1			TEST 2		
	WITHOUT	WITH	P	WITHOUT	WITH	P
Af	32.49(0.28)	31.21(0.75)	(***)	28.49(0.06)	29.65(0.24)	***
Bf	29.89(0.12)	31.86(0.45)	***	30.04(0.22)	29.99(0.07)	NS
Cm	30.47(0.28)	34.45(0.41)	***	33.45(0.11)	33.70(0.42)	**
Dm	34.63(0.07)	35.33(0.11)	***	33.58(0.25)	33.69(0.19)	NS
Em	32.19(0.17)	31.99(0.40)	NS	32.28(0.50)	33.4(0.17)	***

\*  $P < 0.05$  \*\*  $P < 0.01$  \*\*\*  $P < 0.001$

( ) indicates decrease in facial skin temperature

+ m, male; f, female

All subjects showed significant increases in cheek temperature at some stage during the two tests (subject A showed a significant ( $P < 0.001$ ) decrease in mean cheek temperature in Test 1). Only subject C showed consistent increases in both tests. The relative differences in mean cheek temperatures were small (range  $0.11 - 3.98^{\circ}\text{C}$ ).

Table 6.4 shows the mean facial skin temperatures under the respirator (upper lip) with and without the respirator. All subjects showed a significant ( $P<0.001$ ) increase in lip temperature with the exception of subject A in Test 1. There was an overall significant ( $P<0.001$ ) increase in mean skin temperature under the respirator of  $1.5^{\circ}\text{C}$  (mean (sd) without respirator  $32.12(2.27)^{\circ}\text{C}$ ; mean (sd) with respirator  $33.65(1.86)^{\circ}\text{C}$ ).

**Table 6.4 Mean facial skin temperatures (lip) with and without wearing a respirator.**Mean (s.d.)

SUBJECT+	TEST 1			TEST 2		
	WITHOUT	WITH	P	WITHOUT	WITH	P
Af	34.34(0.24)	33.8(0.54)	(**)	30.8(0.29)	32.75(0.35)	***
Bf	29.04(0.27)	31.58(0.35)	***	28.79(0.51)	32.22(0.23)	***
Cm	32.26(0.22)	34.54(0.41)	***	30.77(0.77)	32.74(0.36)	***
Dm	36.38(0.08)	36.75(0.08)	***	34.95(0.36)	35.53(0.20)	***
Em	34.67(0.10)	34.98(0.35)	***	33.24(0.31)	34.77(0.31)	***

\*  $P<0.05$  \*\*  $P<0.01$  \*\*\*  $P<0.001$

( ) indicates decrease in facial skin temperature

+ m, male; f, female

In addition the relative differences in overall skin temperatures between the cheek and upper lip (under the respirator) was significant ( $P<0.001$ ). This indicates that on exercise the rise in skin temperature under the respirator is proportionally greater than the temperature rise to skin exposed to ambient air.

The following Table (Table 6.5) shows the correlation coefficients between the heart rate and skin temperature data for the five subjects. The analysis was between the heart rates recorded for the experimental trials with and without wearing the respirator.

**Table 6.5 Correlation coefficients between heart rate and skin temperature data for the five subjects.** Correlation coefficients are shown for both lip and cheek temperatures and for both tests (Test 1 and Test 2).

Subject	Respirator Worn	Test 1	Test 1	Test 2	Test 2
		Temp (Lip)	Temp (Cheek)	Temp (Lip)	Temp (Cheek)
A	With	0.491	0.904	-0.287	-0.271
	Without	-0.656	-0.697	0.633	0.228
B	With	0.703	0.365	0.509	-0.599
	Without	-0.367	0.457	0.371	-0.281
C	With	0.642	0.643	-0.556	-0.570
	Without	0.551	0.712	-0.460	-0.314
D	With	0.178	0.668	0.253	0.603
	Without	-0.254	-0.073	0.833	0.713
E	With	0.381	0.422	-0.454	-0.495
	Without	0.228	-0.041	0.758	0.678

The results tend to be inconclusive, but indicate positive correlations (range 0.551-0.904) between heart rate and skin temperature (lip and cheek) when the respirator was worn particularly in Test 1. The reverse tends to occur in Test 2 with positive correlations (range 0.501-0.833) between heart rate and skin temperature in three subjects without the respirator. No clear trend can be seen with respect to the negative correlation coefficients.

Ambient air temperatures and observations of subjects physical condition, including sweating and skin colouration are shown in Table 6.6 In addition, comments from the subjects on their subjective perceptions during the experiment were recorded and are shown in Table 6.7

**Table 6.6 Environmental variables and observations of sweating in the experimental tests with and without wearing the respirator.**

Subject	Test Number	Td °C	Twb °C	%RH	Sweating without respirator	Sweating with respirator
A	Test 1	19.0	15.1	62	-	Face
A	Test 2	18.5	15.0	67	-	-
B	Test 1	20.2	15.2	50	-	-
B	Test 2	19.5	15.5	59	-	-
C	Test 1	20.0	15.1	52	-	-
C	Test 2	19.5	15.8	60	-	-
D	Test 1	19.5	15.0	57	Face	-
D	Test 2	21.2	15.8	48	-	-
E	Test 1	19.0	14.0	58	-	-
E	Test 2	18.5	14.0	63	-	Face

Facial sweating was not evident on the subjects in many of the experimental tests, indicating that the subjects were not excessively strained by the level of external work imposed on them (50W on cycle ergometer at 60 revs per minute for 30 minute periods).



**Table 6.7 Comments reported by the five subjects of experimental tests with and without wearing the respirator.**

<b>Thermal Conditions</b>	<b>Breathing Patterns</b>	<b>Respirator</b>	<b>Other Perceptions</b>
Getting hot towards end of test	Felt you had to push air out	Irritation of clicking valve	Didn't notice mask when first put on
Cool when mask put on	Breathing difficult	Valve noise irritating	Began to get headache when mask was on
Stuffy wearing mask	Had to take big breaths	Flapping of valve very apparent	Sense of relief when mask came off
Warm when mask was on	Difference in breathing pattern noticed		
No real difference in temperature	No problem breathing with mask		
Did not feel too hot on the skin			

In addition to comments concerning thermal perceptions and breathing patterns, other comments related to the irritation of hearing and feeling the exhalation valve open and close during breathing, the feeling of relief when the mask was removed and the respirator being associated with one subject reporting a headache.

## 6.4 Discussion

The aim of this experiment was to examine the relationship between heart rate and skin temperature when respiratory protection is worn at a controlled (50W) level of external work. In an attempt to identify any potential gender differences in heart rate or skin temperature response two female subjects were included. No significant differences in mean heart rates between male and female subjects were measured. This is in contrast to the previous chapter (Chapter 5) where differences were evident. The explanation is likely due to the fact that the female subjects were young, fit and physically active, where the male subjects were older and less physically fit. This would, in effect, counteract the relative gender differences in mean heart rate observed by Astrand and Rodahl (1977).

The mean heart rate data recorded during respirator use (Table 6.2) clearly shows the variability of the heart rate response i.e. significant increase, decrease or no difference in mean heart rates. The results are comparable to those recorded in Chapters 4 and 5 of this study and consistent with other studies involving respirator use at light to moderate levels of work (refer reviews by Louhevaara, 1984; Jones, 1991). The very high mean heart rate values recorded by one subject (Dm) at the beginning and in the course of the first experiment (Test 1), can be explained due to psycho-social factors.

The results of the skin temperature measurements are more clearly defined. The increase in cheek temperatures observed in most subjects (Table 6.3) provides evidence of a generalised vasodilation response of the face whilst wearing the respirator. The rise in lip temperatures under the respirator mask (Table 6.4) is likely attributable to both the vasodilation affect and/or the affect of the warm expired air inside the mask increasing the surface skin temperature.

The skin temperature of the upper lip was shown to change significantly when wearing the mask in the present study. Skin temperatures are dependent on the surrounding air temperature (Hardy and DuBois, 1938). Moderate (non extreme) ambient air temperatures recorded in this study were between 18-21°C  $T_d$  and 14-16°C  $T_{wb}$  and the

study demonstrated the sensitivity of the thermal receptors of the face and how the respirator effected the perceptions of the wearer. The comments received from the subjects at the completion of the experiment tended to indicate their general dissatisfaction with the respirator. They could not appreciate how workers in industry could wear them for extended lengths of time. It is of interest that the results from the surveys of use and non-use of respirators (Chapter 2) indicate that many individuals in industrial situations tolerate wearing respirators for very extensive time periods (over 4 hrs per day). The levels of discomfort experienced by these individuals, as reported in comments from survey participants, ranged from mild annoyance to considerable discomfort.

When the relationships between heart rate and skin temperature is examined on a subject by subject basis however (Table 6.5), the results tend to be more enigmatic. The range of correlations obtained ranging from very weak to very strong, is an illustration of the effect heart rate variability has on correlated data. It could be argued that the data could be improved by increasing the number of subjects and that this could provide more conclusive evidence of a heart rate skin temperature relationship.

Although there have been numerous studies on the thermal effects of respirator use and skin temperature on individuals (refer reviews by Louhevaara, 1984 and Jones, 1991) and that heart rate has been accepted as a good indicator of thermal stress (Lind, 1955; Emerson *et al*, 1967; Atterbom and Mossman, 1978; Neilsen *et al*, 1987; Jones, 1991), it is curious that few studies correlating the two variables exist. A number of studies have measured the physiological variables independently (Neilsen *et al*, 1987; Gwosdow *et al*, 1989; White *et al*, 1989; DuBois *et al*, 1990; Jones, 1991). Table 6.8 reviews the data reported in the literature involving respirator use with heart rates and skin temperatures. The type of exercise undertaken and the length of time the test was performed is also indicated. The skin temperatures reported show a narrow range of values of which those recorded in the present study are comparable. The position of the temperature measurement (lip) is common to all the studies, allowing valid comparisons to be made.

**Table 6.8 Summary of the research involving respiratory protection and the effect on heart rates and skin temperatures.** The type of exercise undertaken and duration of the test is indicated.

Skin Temperature (°C)	Type of Exercise	Mean Heart Rate b/min	Reference
28.7 - 34.0 (lip)	Cycle Ergometer (59W for 25 min)	Not Measured	Neilsen <i>et al</i> , 1987
32.5 - 36.0 (Lip)	Seated	Not Measured	Gwosdow <i>et al</i> , 1989
34.7 - 36.4 (lip)	Treadmill (4 kph)	100 - 160	White <i>et al</i> , 1989
32.5 - 35.7 (lip)	Seated	Not Measured	DuBois <i>et al</i> , 1990
Measured but not quoted	Treadmill (20 min)	91 - 136 without 98 - 146 with respirator	Jones, 1991
31.5 - 36.7 (lip)	Cycle Ergometer (50W, 15 min)	85 - 140, mean 110.9(12.7) with 106.2(1.3) with 108.9(13.4) without 105.6(1.4) without respirator *	Present study

\* mean heart rates (sd), males and females

There still appears to be some uncertainty as to how an individual is able to assess thermal sensations and particularly discomfort (Gwosdow *et al*, 1989). The present study tends to confirm that the face is particularly sensitive to thermal stimuli and that small changes in skin temperature are able to be readily detected. In the study by Gwosdow *et al*, (1989), three possible explanations as to how the individual assesses thermal sensation and discomfort from the face are identified:

1. The cutaneous thermoreceptors on the face and upper lip relay information to the thermosensitive structures in the brain and as a result of altering neural transmission, may change the perception of the respirator environment (Gagge, Stolwijk, Hardy, 1967).

2. That a countercurrent heat exchange occurs between venous blood draining the head and arterial blood ascending to the brain. This local heat exchange, would change the temperature of blood perfusing the thermoregulatory centres of the brain, which in turn, would change the perception of the respirator thermal environment (Cabanac and Caputa, 1979).
  
3. That venous blood returning from the nasal cavities to the thermosensitive structures in the brain may affect the perception of the thermal environment (Caputa, Perrin and Cabanac, 1978).

Gwosdow *et al*, (1989) suggested that it is possible that the respirator conditions studied influenced skin temperature by one or more of these mechanisms. DuBois *et al*, (1990), suggest that the mechanism of discomfort may be related to thermal sensation, sweating and hydration, condensation of expired water vapour, cutaneous bloodflow, or vascular congestion, or all of the above. They also concluded that the weight of the devices brought about some discomfort, although the overriding factor related to the temperature of the face under the mask. The results of the present study tend to support the explanations that involve cutaneous thermoreceptors and the sensitivity of their response to external stimuli.

It has been demonstrated that sensations of facial skin temperature, sweating and discomfort increased in direct proportion to an increase in facial skin temperature as measured with a thermocouple under the respirator (DuBois, Harb and Fox 1990). Skin temperature of the face was measured on the nasolabial fold of the upper lip. The effect of three different types of half-facepiece air-purifying respirators were assessed in this study. They demonstrated that the masks were comfortable when the skin temperature of the face was 33°C or less and became slightly uncomfortable at a skin temperature of 35°C. These findings are comparable with previous data obtained using masks with a continuous air flow (Gwosdow *et al*, 1989).

In conclusion, evidence from the current study supports the view that:

- (i) A small (mean 1.5 °C increase) but significant increase in facial skin temperature occurs when wearing a respirator in the environmental conditions that occurred in the present study.
- (ii) It appears that the critical skin temperature range for sensations of discomfort is between 34 - 35 °C. Discomfort conditions were reported in this study by subjects with skin temperatures below or approaching these values.
- (iii) The temperature rise was not only significant under the respirator (upper lip), but also occurs in the localised areas around the respirator (cheek), indicating some general facial vasodilation. It is well known that the face - in particular the cheeks and forehead are said to be the regions of the body most sensitive to warm stimuli (Stevens, Marks and Simonson, 1974).
- (iv) The data also provides evidence that very small changes in facial skin temperature are detected by respirator users and that this is an important cue for feelings of discomfort. All of the subjects of the study commented that the respirator felt hot or warm when worn and were relieved when it was removed. This adds support to the theory that local heating may have a significant role in respirator unacceptability.
- (v) Other perceptual cues including an awareness of the respirator valves 'flapping' during inhalation and exhalation also provide evidence of heightened subjective responses to the presence of the respirator.
- (vi) An awareness of the individual's breathing and breathing pattern also was identified (as in Chapter 5) as another important factor of respirator tolerance.

## CHAPTER 7

### 7.0 WORK ENVIRONMENT STUDY

#### 7.1 Introduction

There have been few reported studies of field investigations undertaken to assess the level of external work or cardiorespiratory strain in activities that require the use of respiratory protection (refer reviews by Raven *et al*, 1979 and Louhevaara, 1984; Louhevaara *et al*, 1985). Early Swedish research by Zylberstein (1973) and Holmer and Arvidsson (1975) investigated self contained breathing apparatus used during fire fighting. These authors reported that wearing the equipment and undertaking many of the tasks required during fire fighting, imposed a maximal or near maximal physiological stress on the subjects. Later work by Louhevaara *et al*, (1985), evaluated the consequences of wearing breathing apparatus, air-purifying and air-supplied respiratory protection. Heart rates were recorded and, where technically possible, oxygen consumption and minute ventilation, from 30 male subjects from a variety of industries.

Results from Louhevaara *et al*, (1985) confirmed that fire fighting tasks wearing SCBA and protective clothing was physically very demanding requiring oxygen consumption values of 2.1 to 2.8 l/min (54-75%  $\dot{V}O_{2\max}$  for their subjects). For fire fighters involved in smog-diving, repair and rescue tasks whilst wearing self contained breathing apparatus, mean heart rate values were reported from 142 to 160 beats/min (62-78% HRR and 54-74%  $\dot{V}O_{2\max}$ ). Mean minute ventilation values were correspondingly 45 to 70 l/min. The authors concluded that these tasks imposed considerable physiological strain on individuals and that accordingly, work times should be limited to 1 to 2 work tasks per workshift of 8hr with SCBA (Louhevaara *et al*, 1985).

Louhevaara *et al*, (1985) also recorded mean heart rates recorded during work requiring air-purifying devices (demolition work, foundry work, spray painting, welding) were from 69-111 beats/min (13-35 %HRR). In the heaviest work phases of

these activities, heart rates rose to 86 to 144 beats/min (27-67 %HRR). The mean oxygen consumption values measured were 0.49 to 1.04 l/min with corresponding minute ventilation values of 16 to 33 l/min. The length of time the devices were worn varied with tasks and was between 10mins - 6 hrs. The authors concluded that the measures of strain varied widely but manual demolition work (mean heart rates >111 b/min, mean oxygen consumption >1.33 l/min) was particularly heavy work.

Interestingly, similar values for heart rate were recorded for industrial tasks that required air-supplied devices (sand blasting, metal spraying). The mean heart rate values varied from 69 to 111 beats/min, with the highest recorded values being from 92 to 136 beats/min (Louhevaara *et al*, 1985).

A number of laboratory studies have examined the effect respirator use has on heart rate and skin temperatures. Neilsen *et al*, (1987), investigated the subjective and physiological responses of six subjects in a laboratory. Different combinations of ambient air temperatures and mask temperatures were studied. Skin temperatures, heart rates and skin wettedness were monitored during exercise. The subjects' acceptance of the mask and the thermal environment, thermal sensation, sensations of discomfort, sweating and skin wettedness were assessed. Heart rates measured during the exercise periods averaged 112 b/min and were found to be independent of both ambient and mask air temperature. No correlations in regard to skin temperature and heart rate were undertaken in the study.

Gwosdow *et al*, (1989) examined the physiological and subjective responses in six sedentary subjects wearing half-facepiece respirators in the laboratory. Physiological measurements included local skin and dew-point temperatures. Heart rates were not recorded in the experiment. Subjective judgements of acceptability, thermal sensation, degree of discomfort, sense of skin moisture and difficulty breathing were recorded. Acceptability of the respirator decreased markedly as lip temperature increased above 34.5 °C.

Similarly, White *et al*, (1989) studied the physiological and subjective effects of



working with different respirators while wearing lightweight disposable overalls, commonly used in the asbestos abatement industry. Nine subjects performed a series of exercise tests with four different respirator ensembles in the laboratory. Physiological measurements obtained during each test included heart rate, skin and rectal temperatures. Subjective evaluations of discomfort, difficulty breathing and workload were also made. Analysis of variance were undertaken between respirator types, for heart rate, skin and rectal temperatures.

More recently, DuBois *et al.*, (1990), measured skin temperature and subjective responses to wearing three different types of half-facepiece respirators in six men and six women in a room maintained at 25 °C. The subjects reported that the face felt comfortable when skin temperature was 34 °C or below. As the skin temperature rose above 34.5 °C, the face felt increasingly warm, uncomfortable and sweaty. No measurement of heart rate was undertaken in the study.

In contrast, Jones (1991) measured heart rate, respiratory rate, blood pressure, air temperature inside the respirator, resistance to breathing and heat stress imposed on ten subjects wearing disposable respirators. Skin temperature was not measured.

Most physical work in industry is intermittent and a steady state is rarely attained. The classical laboratory studies, with subjects exercising continuously for 5 minutes or longer on a cycle ergometer, in many ways represent a very artificial situation in which to model what happens in industry. Nevertheless, such procedures have distinct advantages when one is studying the physiology of exercise, for they provide standardised conditions and permit comparisons to be made on repeated occasions or between laboratories. They may also simulate the demands placed on the body in many situations, for example endurance sports (Astrand and Rodahl, 1977).

It is important in the study of the physiological cost of wearing respiratory protection, to measure firstly, the 'physiological cost' of the work task on an individual and then to determine to what degree the use of the respirator imposes an additional cost on the wearer. The aim of this section of the current study is to attempt determine the level

of work normally undertaken by individuals that are expected to wear respirators in New Zealand industry and tabulate the extent to which the use of a respirator imposes an additional burden on the user during actual work situations.

The objectives of the study were therefore to (i) determine the heart rates of a group of individuals working in industry in the Palmerston North area who are required to wear respiratory protection, (ii) determine the relative differences in heart rate and facial skin temperature whilst performing the same task with and without wearing a respirator.

## 7.2 Material and Methods

The collection of data was carried out during spring (October and November) and early summer (December) 1993.

### 7.2.1 Subjects

A total of twelve subjects were used in the present study. The subjects were individuals selected from a survey of respirator users in the Palmerston North area (Chapter 2). Their selection was dependant on the type of work undertaken and their responses to the question concerning their perceived work load i.e. heavy, moderate or light. Four subjects from each of the self reported groups were chosen for this study.

The characteristics of the twelve male volunteer subjects, in terms of their age, height, weight are shown in Table 7.1. Means and standard deviations (s.d.) for age, height and weight of the subjects are presented.

**Table 7.1 Physical characteristics of volunteer subjects**

Subject	Age(yrs)	Height(cm)	Weight(kg)
1	39	180	80
2	37	175	96
3	29	168	72
4	42	185	77
5	30	176	65
6	28	182	68
7	45	172	64
8	34	188	79
9	44	177	74
10	22	184	82
11	31	171	68
12	39	180	75
Mean	35	178.1	75
s.d.	7.15	6.1	8.8

### 7.2.2 Measurements and Techniques

Each subject was asked to wear a four channel 'Socially Acceptable Monitoring Instrument' (SAMI) during part of a work period. The SAMI consists of a miniature (size 11 by 9 by 3.5 cms; weight 400 gm) four channel, body borne tape recorder (Oxford Instruments Medilog Series 4.24, Cambridge, England).

Facial skin temperatures were recorded on two channels (Channels 1 and 2) of the SAMI via two bead thermistors (NTC thermocouples) bonded to two 15 mm alloy plates. One thermistor and plate was positioned 20 mm anterior to the external auditory meatus (on the cheek) and the second was placed directly below the left nare on the upper lip. The thermistors were calibrated against a mercury glass thermometer by immersion in a water bath with varying temperatures from 30.0 to 40.0 °C. The accuracy of the thermistors was between  $\pm 0.5$  °C ( $T_{\text{cheek}}$ ) and  $\pm 0.6$  °C ( $T_{\text{lip}}$ ). The fourth channel was used as a calibration timing channel. The timing channel produced pulses at 10 second intervals throughout the recording sequence.

Heart rate was recorded using a Sports Tester PE 3000 (Polar Electro, Finland) recording heart rates every 15 seconds. The Sports Tester PE 3000 was calibrated against a standard isolated ECG amplifier and cardiac ratemeter (Jrak BioSignals Ltd., Windsor, Vic., Australia) and found to be accurate to within  $\pm 1.0\%$ .

Data obtained from analysis of the SAMI tapes, using a playback tape system (Oxford Instruments, Cambridge, England), were skin temperature under the mask (lip) and facial skin temperature (cheek). Heart rate data were down loaded manually and readings obtained were recorded against the time of sampling.

### 7.2.3 Experimental Design

The protocol for the study involved the subjects being asked firstly to 'simulate' their work activity whilst wearing the heart rate monitor and the thermistors but not the respirator. The 'simulated' work was undertaken at the place of work with the subject

performing all the movements and postures associated with completing the task. They were then asked to repeat the same activity whilst wearing the respirator. i.e to undertake the 'actual' work task at the place of work. Recordings of heart rate and skin temperature were taken continuously throughout the periods of simulated and actual work. The rationale for using a work simulation in this study is based on the need for data on the physiological strain of the work task without exposing the subjects to the hazards of the workplace. The only way to achieve this is by requiring the subject to simulate as precisely as possible the exact work activities required for the task, which were recorded. Major muscle mass movements and postural attitudes were recorded at specific times during the activity.

It is acknowledged that although the protocol is not ideal, the method is an attempt to obtain data on the physiological cost of actual work activities. The activities involved in the work task simulation were undertaken to represent as near as possible the actual work activities. Every effort was made to maintain a 'normal' work environment and disruptions to work activities and tasks were kept to a minimum. It was considered that any further disruption of the work task would create artificial conditions that would not be representative of the 'actual work'. In addition the interruption of work activities for extended periods of time was not desirable from a management and a research perspective.

#### 7.2.4 Activity Recording

Details of the type of activity, postures and time taken to perform the activities were recorded in an activity diary for each subject. The task was continuously observed and details of the activity were recorded against a time scale. The activities could then be compared with the recorded heart rate and skin temperatures.

#### 7.2.5 Environmental Variables

The thermal environment was measured at the place of work before the simulated task and after the actual work task was completed. Ambient air temperature and relative

humidity were measured using a standard whirling hygrometer. Radiant heat was measured with a globe thermometer (Cassella, England). Air velocity was measured using a hot wire anemometer TA 3000 (Air Flow Instruments, England).

#### 7.2.6 Statistical Analysis

HRmax is estimated from the formula by Jones (1988):  $210 - 0.66 \text{ Age}$ .

The percentage heart rate range (% HRR) formula was taken from Louhevaara *et al*, 1985, in which %HRR is calculated using the formula:

$$\%HRR = \frac{HR_{\text{work}} - HR_{\text{rest}}}{HR_{\text{max}} - HR_{\text{rest}}} \times 100$$

Descriptive statistics were used to describe all the data (Minitab Inc, Release 8.2, 1991) and a paired t-test used to compare measurements on the individual subjects with and without the respirator. Standard P values of 0.05, 0.01 and 0.001 were used to determine statistical significance. Due to the wide variety of work activities studied with only 2 subjects undertaking each activity, pooled data was considered to be invalid and individual results are presented.

### 7.3 Results

The range of work activities chosen from information gathered in the respirator usage survey (Chapter 2), provided a comprehensive selection of tasks carried out wearing respirators in the region. The hazards associated with these tasks included exposure to chemicals in solid, mist and vapour phases and dusts in fibre and particulate form. The types of respiratory protection used ranged from disposable dust masks to half-mask respirators with vapour cartridges and prefilters. Safety overalls were used by over half of the subjects, with the remainder wearing dust coats or work clothes. Ambient temperatures ( $T_d$ ) ranged from 17 - 24 °C at the time the experiments were undertaken. Table 7.2 shows the subjects' work activity, the type of respirator worn, work clothing and other equipment worn or used and the ambient temperature at the time of measurement.

**Table 7.2 Subjects' work activity, type of respirator and other clothing and air temperature.**

Subject	Work activity	Type of respirator	Clothing/Equip	Ambient Temp(°C)
1	Chemical Spraying	3M 7281 Easibreath	Overalls	20 - 24
2	Chemical Spraying	3M 7281 Easibreath	Overalls	18 - 22
3	Paint Spraying	Protector (Single)	Dust Coat	18 - 20
4	Paint Spraying	Protector (Twin)	Overalls	19 - 22
5	Furniture maker	3M Dust mask	Dust coat	18 - 20
6	Furniture maker	3M Dust mask	Dust coat	19 - 20
7	Chemical mixing	Kemira Silner	Overalls	17 - 19
8	Chemical mixing	Moldex 2200	Overalls	19 - 21
9	Sanding fibreglass	3M Mask 6985	Work cloths	18 - 20
10	Sanding fibreglass	3M Mask 6985	Workcloths	19 - 21
11	Panelbeating	3M Easibreath	Overalls	17 - 19
12	Panelbeating	Kemira Silner	Overalls	18 - 20

The mean age of the subjects (mean 35 (7.1) yrs) is typical of field studies where subjects are from a mature work force (in contrast to many experimental studies using students as subjects). All of the subjects reported using respiratory protection in their work activities for over 3 months. Four subjects indicated they have used respirators each working day for the last 3 years.

### 7.3.1 Description of Work Activities

Table 7.3 shows the work activities undertaken by the subjects, the duration of the task observed, the number of times the tasks is performed per shift and the total length of time the respirator would be worn per shift.

**Table 7.3 Summary of work tasks, the length of time taken to perform the task and the length of time the respirator is estimated to be worn per shift.**

SUBJECT	Work task	Task Duration (mins)	No tasks/shift	Time worn/ shift (mins)
1	Chemical spraying	20	4	80
2	Chemical spraying	30	4	120
3	Paint spraying	12	6	72
4	Paint spraying	21	6	126
5	Furniture maker	7	10	70
6	Furniture maker	5	10	50
7	Chemical mixing	13	5	65
8	Chemical mixing	12	5	60
9	Sanding fibreglass	11	8	88
10	Sanding fibreglass	10	8	80
11	Panelbeating	27	4	108
12	Panelbeating	24	4	96



The first pair of subjects (#1 and #2) undertook spraying of agricultural chemicals using an air-pressure back pack. The work activity involved assembling and filling a spray container and walking to the position where the spray is applied. This involved pumping the lever of the air-pressure back pack a number of times to generate sufficient pressure to enable spraying, then directing the hose and spray head in the areas requiring spraying. Movements involved bending, twisting, stretching and walking.

The second pair of subjects (#3 and #4) were involved in paint spraying furniture using pressurized air hose and paint reservoir. The work activity involved maintaining relatively static positions, with use of predominantly lower and upper arms.

The third pair of subjects (#5 and #6) were furniture manufacturers whose work activity involved cutting, planing and sanding wood. A variety of equipment was used by the subjects and the respirator remained on the face as the subjects moved from one machine to the other. The work periods were of short duration (5-7 mins). The work involved generally static positions, with some movements from one machine to another. The lower and upper arms were the parts of the body most frequently used.

The fourth pair of subjects (#7 and #8) undertook mixing chemicals in a variety of containers. The chemicals were contained in bags which were carried to the mixing position, opened and poured into the mixing vessel. Some manual mixing was observed, although most processes had some form of automated mechanical mixing device. Body movements involved lifting, carrying, twisting, bending and arm rotation. The lower and upper arms were used predominantly, with occasional body twisting and bending.

The fifth pair of subjects (#9 and #10) were involved in sanding precast fibreglass moulds. The work environment was particularly dusty as the activity produced a fine particulate in the air. Work activities ranged from mould positioning, sanding and cleaning. Body movement was predominantly use of the arms and shoulders, with

occasional trunk lowering and turning.

The sixth pair of subjects (#11 and #12) were panelbeaters, whose work involved preparing and spraying automotive body parts. The work activity involved some considerable movement of the arms, shoulders and trunk and constrained and awkward postures were evident in some tasks. This was due to nature of the spraying task which involved spraying car panels that were relatively low to the ground. One subject (#12) was required to lie on the workshop floor to complete a panel. The ambient air temperature was warm and the subjects were perspiring freely.

Heart rate and skin temperature records for the twelve subjects during simulated and actual work tasks are found in Appendix 7. The following table (Table 7.4) shows the mean heart rate and skin temperatures for the lip and cheek of the twelve subjects. The statistical tests are for the mean differences between the wearing and not wearing the respirator.

**Table 7.4 Mean values for cheek (Tc) and lip (Tl) temperatures (°C) and heart rates (b/min) for subjects wearing and not wearing respiratory protection during simulated and actual work activities.**

Subject	<u>No Respirator</u>			<u>Respirator Worn</u>		
	mean Tc (°C)	mean Tl (°C)	mean HR	mean Tc (°C)	mean Tl (°C)	meanHR
1	32.7(0.4)	32.4(3.4)	94.2(2.3)	32.5(0.3)	34.8(1.05)	95.0(2.2)
2	32.2(0.34)	32.1(0.36)	77.3(2.63)	32.5(0.3)	34.9(0.95)	78.4(3.7)
3	33.1(1.29)	34.0(1.46)	75.2(8.74)	34.6(0.41)	35.9(0.75)	77.7(7.5)
4	32.6(0.9)	32.4(0.2)	93.7(2.76)	32.4(0.25)	35.0(0.95)	96.9(2.9)
5	32.4(0.79)	32.9(0.47)	77.8(4.45)	34.1(0.15)	34.1(0.53)	77.0(3.6)
6	34.3(0.19)	32.4(0.34)	82.2(2.77)	33.9(0.11)	33.8(0.83)	78.6(2.7)
7	30.1(1.47)	31.8(0.94)	81.6(2.07)	30.4(0.45)	33.2(0.55)	84.0(3.4)
8	32.4(0.25)	30.7(0.88)	80.1(2.95)	32.3(0.21)	32.2(0.46)	80.3(2.1)
9	31.4(0.32)	32.1(0.18)	83.4(3.2)	30.4(0.20)	31.5(0.24)	85.1(0.2)
10	30.8(0.14)	29.9(0.49)	79.6(1.3)	31.5(0.59)	31.4(1.11)	83.5(2.5)
11	30.7(0.69)	30.5(0.69)	93.7(2.4)	30.9(0.47)	35.3(1.23)	98.2(3.1)
12	30.1(0.95)	31.2(1.4)	93.6(2.0)	30.9(2.0)	35.7(1.36)	95.7(1.6)

( ) indicates decrease

\*\*\* P<0.001

\*\* P<0.01

\* P<0.05

### 7.3.2 Mean Heart Rates

The following table (Table 7.5) shows the mean heart rates ( $\pm$  standard deviation) for the simulated and actual work tasks, the resting heart rates for the subjects and the ratio of resting to working heart rates.

**Table 7.5 Mean heart rates for the twelve subjects at work and at rest and the relative heart rate ratios.** HRw is mean work heart rate (b/min); HRr is mean resting heart rate (b/min); Ratio is mean ratio of HRw to HRr.

SUBJECT	HRw(b/min)	HRw(b/min)	HRr (b/min)	RATIO	RATIO
	Simulated	Actual		Simulated	Actual
1	94.2(2.3)	95.0(2.2)	88	1.07	1.08
2	77.3(2.6)	78.4(3.8)	69	1.12	1.13
3	75.2(8.7)	77.7(7.6)	69	1.09	1.12
4	93.7(2.7)	96.9(2.9)	82	1.14	1.18
5	77.9(4.7)	77.0(3.6)	69	1.13	1.11
6	82.2(2.7)	78.6(2.7)	71	1.16	1.11
7	81.6(2.0)	84.0(3.4)	71	1.15	1.18
8	80.1(2.9)	80.3(2.1)	69	1.16	1.16
9	83.4(3.2)	85.0(0.2)	74	1.12	1.15
10	79.6(1.3)	83.5(2.5)	72	1.10	1.16
11	93.7(2.4)	98.2(3.1)	70	1.33	1.40
12	93.6(2.0)	95.7(1.6)	71	1.32	1.34

Table 7.6 shows the estimated maximal heart rates and percentage heart rate range (%HRR) for the twelve subjects.

**Table 7.6 Subjects' estimated maximal heart rates and cardiorespiratory strain of the work task as determined by the percent of heart rate range (%HRR).** HRmax is estimated from the formula by Jones (1988):  $210 - 0.66 \text{ Age}$ ; percentage of heart rate range (%HRR) is calculated using the formula in the methods (section 7.2.6). (Actual= with respirator; Sim.= simulated, without respirator).

SUBJECT	HRmax (b/min)	HRr (b/min)	HRw Actual (b/min)	HRw (Sim) (b/min)	%HRR Actual	%HRR (Sim)
1	184	88	95.0	92.4	7.3	6.4
2	186	69	78.4	77.3	8.0	7.1
3	191	69	77.7	75.2	7.1	5.1
4	182	82	96.9	93.7	14.9	11.7
5	190	69	77.0	77.9	6.6	7.3
6	191	71	78.6	82.2	6.3	9.3
7	180	71	84.0	81.6	11.9	9.7
8	187	69	80.3	80.1	9.6	9.4
9	181	74	85.0	83.4	10.3	8.7
10	195	72	83.5	79.6	9.3	6.2
11	189	70	98.2	93.7	23.7	19.9
12	184	71	95.7	93.6	21.8	20.0

### Subjects 1 & 2

Mean heart rates for subjects 1 and 2 showed no significant differences when the respirator was worn. Heart rates were relatively stable for both subjects and heart rate recordings showed minimal variation. Walking and spraying constituted most (80%) of the work time for the task. Noticeable increases in heart rate were recorded every 3-4 minutes when Subject 2 used the pump lever to pressurise the chemical spray container (mins 5, 8, 12, 16, 18, 22, 25, 30 and 34).

### Subjects 3 & 4

Mean heart rates for Subject 3 showed no significant difference when the respirator was worn. Heart rates for Subject 3 varied widely (mean 75.2 sd 8.7 simulation; mean 77.7 sd 7.57 actual work task). Heart rate was noticeably elevated during equipment failure episodes (spray nozzle blocked between min 15-17 in the simulation) and when putting on the respirator (min 25-27).

Mean heart rates for Subject 4 showed a significant ( $P < 0.05$ ) increase when the respirator was worn. The heart rate recordings for Subject 4 were stable showing little fluctuation. Spraying paint using lower and upper arms in static positions was the main activity involved in the task (90% task time). Noticeable increases in heart rate were observed when Subject 4 leaned to spray under a furniture seat (min 8 in simulation; mins 22-23 in actual task).

### Subjects 5 & 6

Mean heart rates for Subjects 5 and 6 showed no significant difference when the respirator was worn. Heart rates showed minimal fluctuations during the simulated and actual work task. The primary activity during the task was the use of portable sanding equipment (71% task time Subject 5; 60% task time Subject 6). Noticeable increases in heart rate were observed when the respirator was about to be placed on the subjects' face (mins 5 and 6).

### Subjects 7 & 8

Mean heart rates for Subject 7 showed a significant ( $P < 0.05$ ) increase when the respirator was worn. Heart rate recordings for Subject 7 were stable, except for mins 7-8 (simulation) and mins 17-18 (actual work task). In both instances the subject was required to bend to mix materials in a vessel. Mean heart rates for Subject 8 showed no significant differences when the respirator was worn. Elevations in heart rate occurred when the subject mixed the chemicals in a vessel manually using a ladle (min 7 simulation; min 23 actual work task). Observation was the activity most frequently recorded during the mixing task (70% task time Subject 7; 80% task time Subject 8).

### Subjects 9 & 10

Mean heart rates for Subject 9 showed no significant difference when the respirator was worn. The activity record indicated using the sander elevated heart rates in both simulated and actual work activities (mins 4-5 simulation; mins 14-15 actual work task). This involved circular movements of arms and upper body and was the most frequent activity recorded (58% task time Subject 9; 70% task time Subject 10). Mean heart rates for Subject 10 showed a significant ( $P < 0.001$ ) increase during respirator use. A noticeable elevation in heart rate was observed when the respirator was placed on the face of the subject (mins 10-11).

### Subjects 11 & 12

Mean heart rates for both subjects showed a significant ( $P < 0.001$ ) increase when the respirator was worn. Heart rate recordings were relatively stable and showed minor fluctuations. The activity analysis recorded spraying as the activity which involved the most time in the task (90% task time Subjects 11 and 12). Subject 12 was required to lie under the vehicle for a short (30 sec) period (min 16 in simulation; min 42 in actual work task).

### 7.3.3 Skin Temperatures

Mean skin temperatures for the lip and cheek during simulated and actual work tasks are shown in Table 7.4. During actual work tasks when the respirator was worn, significant differences ( $P < 0.05$ ) in facial skin temperature between the cheek and the lip (under the mask) were observed in six of the twelve subjects (subjects #1, #2, #4, #7, #11, #12). In addition, significant increases in lip temperature ( $P < 0.01$ ) were observed in all but one (Subject 9) of the subjects when wearing the respirator during actual work tasks (Table 7.4). A noticeable delay of approximately 3 minutes occurred before the skin temperature approached its mean value in a number of subjects (#1, #2, #3, #4, #9, #11, #12).

Subjects 1 and 2 showed in excess of a 2 °C increase in mean lip temperature when the respirator was worn (increase of 2.4 °C Subject 1; increase of 2.8 °C Subject 2). The difference was significant ( $P < 0.001$ ). Mean cheek temperatures in the simulated and actual work tasks remained stable and showed minor fluctuations with no significant differences.

Subject 3 showed increases in both cheek and lip mean temperatures when the respirator was worn (mean increase 1.5 °C cheek temp; mean increase 1.9 °C lip temp). The differences were significant ( $P < 0.001$ ). Subject 4 showed a mean increase in lip temperature of 2.6 °C when the respirator was worn. Mean cheek temperatures remained constant throughout the simulation and actual work tasks.

Subject 5 showed significant increases in both mean cheek and lip temperatures (mean increase of 1.9 °C cheek temp; mean increase of 1.2 °C lip temp) when the respirator was worn. The temperatures recorded for both the cheek and lip were very similar (Table 7.4). No noticeable increase was evident from the temperature recordings. Subject 6 showed a significant ( $P < 0.05$ ) decline in mean cheek temperature of 0.4 °C and a significant ( $P < 0.01$ ) increase in mean lip temperature of 1.4 °C when the respirator was worn. Cheek temperatures for this subject during the simulation were significantly higher than lip temperatures.



Subjects 7 and 8 showed an increase of approximately 1.5 °C in mean lip temperature when the respirator was worn (increase of 1.4 °C Subject 7; increase of 1.5 °C Subject 8). The differences were significant ( $P<0.01$ ,  $P<0.05$ ). Mean cheek temperatures in the simulated and actual work tasks for Subject 7 showed some variation. Noticeable elevations in cheek and lip temperatures were observed when the subject bent over the vessel in the simulated mixing task (mins 8-10 simulation). Mean temperatures for Subject 8 remained stable and showed minor fluctuations with no significant differences. A noticeable increase in lip temperature was observed when the subject used a ladle for mixing in the work simulation (min 11-13 simulation)

Subject 9 showed a significant ( $P<0.001$ ) decline in both cheek and lip temperatures when the respirator was worn. Skin temperatures for Subject 10 showed a mean increase of 0.7 °C in cheek temperature and 1.5 °C rise in lip temperature. Both increases were significant ( $P<0.001$ ).

Subjects 11 and 12 both had substantial increases in mean lip temperature when the respirator was worn (increase of 4.8 °C Subject 11; increase of 4.5 °C Subject 12). These differences were significant ( $P<0.001$ ) in both cases. Subject 11 also showed a significant ( $P<0.001$ ) increase in mean cheek temperature of 0.8 °C as a result of respirator use. Mean cheek temperatures for Subject 11 in the simulated and actual work tasks remained stable and showed minor fluctuations with no significant differences .

The following Table (Table 7.7) shows summary data of the significant changes in heart rate and skin temperature as a result of wearing respiratory protection.

**Table 7.7 Overall changes in mean heart rates, lip and cheek temperatures for the twelve subjects.**

SUBJECT	Change in Mean HR (b/min)	Changes in Mean Temp (cheek) °C	Changes in Mean Temp (lip) °C
1	-	-	2.4 ***
2	-	-	2.8 ***
3	-	0.6 ***	1.9 ***
4	3.2 *	-	2.6 ***
5	-	1.5 **	1.2 **
6	-	(0.4) (*)	1.4 *
7	2.4 **	-	1.4 **
8	-	-	1.5 ***
9	-	(1.0) (***)	(0.6) (***)
10	3.9 ***	0.7 **	1.5 **
11	4.5 ***	-	4.8 ***
12	2.1 ***	0.8 ***	4.5 ***

( ) indicates decrease

\*\*\* P<0.001    \*\* P<0.01    \* P<0.05

The Table shows five of the twelve subjects had significant increases in mean heart rate as a result of respirator use. Four subjects exhibited increases in cheek and lip temperatures indicating general facial warming. Eleven of the twelve subjects however, had significant increases in lip temperature with respirator use. The remaining subject showed a decline in lip temperature. This result appears anomylous and may be explained by the subject’s proximity to the open entrance of

the factory. The external environmental temperatures were lower than those within the factory and some cooling effect may have occurred. Four subjects showed a significant increase in cheek temperature. Two subjects had falls in cheek temperature due to respirator use.

## 7.4 Discussion

Although the experimental design of the study was not ideal as mentioned in the methods (Section 7.2.3), it is encouraging that the results of the heart rate measurements between the simulated and actual work tasks showed a close relationship. This is evidenced by the heart rate ratio values (Table 7.5). This supports the contention that the physiological strain of the simulated work tasks undertaken by the subjects were not dissimilar to the strain of the actual work tasks and therefore measures of relative skin temperatures with and without the respirator were valid.

The results also confirmed that respiratory protection is worn for extended periods of time during the work shift (Table 7.3). Even though the task using the respirator in some instances is relatively short (e.g. 5-7 minutes for Subjects 5 and 6) the number of times the task is performed during the shift in total may be considerable (e.g. 10 tasks per shift). The length of time the respiratory protection was worn by the subjects in the present study (between 1 - 2 hours per shift) corresponds to 10 to 25% of total shift time. These values are comparable to those recorded by Louhevaara *et al*, (1985), who found respirator use times for the work activities evaluated ranged from 29 minutes (0.5 hours, 6% total shift time) per shift for foundry spray painters, to 314 minutes (5.2 hours, 60% total shift time) for foundry cast cleaners and welders.

The results of the present study are also consistent with results obtained by Louhevaara *et al*, (1985), who showed that physiological strain in jobs requiring filtering devices as measured by mean heart rates varied widely (12-62 %  $\dot{V}O_{2\max}$ ) among the jobs studied. These were primarily manual demolition workers, foundry workers, shipyard workers, metal industry workers.

It is important to note that the heart rate changes that did occur in the present study were relatively small and whether they were significant or not to an extent depended on the stability (i.e. variability) of the subjects heart rate.

The following Table (Table 7.8) summarises the mean work heart rates and percentage heart rate ranges for the work activities involving the use of air-purifying respirators evaluated by Louhevaara *et al*, (1985) and compares the values recorded in the present study.

**Table 7.8 Summaries of data reported in earlier research on mean heart rates and percent heart rate ranges for a variety of work tasks.**

WORK TASK	Mean HR <sub>work</sub>	% HRR	Reference
Construction work	99 - 132	37 - 57	Louhevaara et al 1985
Foundry work	83 - 96	13 - 25	" "
Spray painting	110 - 111	34 - 35	" "
Welding	71 - 81	15 - 17	" "
Shipyard work	66 - 101	15 - 31	" "
Ag. chemical spraying	78 - 95	7.3 - 8.0	Present study
Furniture spraying	77 - 97	7.1 - 14.9	" "
Sanding/ cutting wood	77 - 79	6.3 - 6.6	" "
Chemical mixing	80 - 84	9.6 - 11.9	" "
Fibreglass sanding	83 - 85	9.3 - 10.3	" "
Panelbeating	95 - 98	21.8 - 23.7	" "

The % HRR values (Table 7.8) indicate that the relative cardiorespiratory strain of all of the tasks evaluated, except for panelbeating tasks, is light (6.3 - 14.9 % HRR). Panelbeating activities were shown to have comparable % HRR values to shipyard work i.e. spray painting, painting of engine parts and repair painting (Louhevaara *et al*, 1985). This appears consistent as the detailed work activities of these tasks would be similar to panelbeating tasks.

When the values for the ratio of working heart rate to resting heart rate were compared to earlier studies (Minard *et al*, 1971; Fordham *et al*, 1978; Goldsmith *et al*, 1978; Vitalis *et al*, 1994) it was evident that the tasks assessed in the present study, with the exception of panelbeating were light. Using the heart rate ratio values to assess strain, the panelbeating tasks could be considered moderate. Table 7.9 summarises the ratio of working heart rates to resting heart rates in the studies referred to above.

**Table 7.9 Summary of heart rate ratios for the work tasks evaluated in earlier studies compared to the present study.** Ratio is mean ratio of HR<sub>w</sub> to HR<sub>r</sub> (standard deviation).

WORK TASK	No. OF SUBJECTS	RATIO	REFERENCE
Open hearth workers	19	1.64	Minard <i>et al</i> , (1971)
Nurses	14	1.45	Fordham <i>et al</i> , (1978)
Car assembly workers	20	1.45	Goldsmith <i>et al</i> , (1978)
Cane cutters	8	1.38 (0.12)	Vitalis, (1981)
Steel workers	19	1.37 (0.23)	Vitalis <i>et al</i> , (1994)
Ag. chemical sprayers	2	1.1 (0.03)	Present study
Paint spraying	2	1.1 (0.04)	" "
Furniture maker	2	1.1 (0.0)	" "
Chemical mixing	2	1.2 (0.01)	" "
Sanding fibreglass	2	1.2 (0.01)	" "
Panelbeating	2	1.37 (0.04)	" "

It is important to note in this Table (Table 7.9) that the earlier studies, with the exception of Vitalis *et al*, (1994) and the present study, all measurements of HR<sub>r</sub> used

sleeping heart rates as resting values. Vitalis *et al*, (1994) have suggested that using a resting as opposed to a sleeping heart rate would likely underestimate the ratio values, as the sleeping heart rates are likely to be lower during slow wave sleep than the 'at rest' measurements.

The present study attempted to assess a range of work tasks requiring the use of respirators and as a consequence, the number of subjects in the work tasks evaluated were relatively small (2 subjects per activity). It can be argued that little can be gained from the results because of this fact. However, an important feature of this study was its inter-relation to the earlier survey of respirator use and non-use (Chapter 2). It was reported by many respirator users that the perceptions of their workloads played an important part of the reasons for non-use of the devices in particular. Many of the subjects of the present study (8 out of the 12) indicated that their workloads were moderate to heavy. The results of the present study tend to dispute these perceptions.

Although there have been numerous studies on the thermal effects of respirator use on individuals (refer reviews by Raven *et al*, 1978 and Louhevaara, 1984; Jones, 1991), few have been undertaken in actual work environments. As heart rate is an accepted as being a good indicator of thermal stress (Atterbom and Mossman, 1978; Jones, 1991) it is interesting to observe that few published studies on the thermal effects of respirator use have examined heart rate in relation to skin temperature.

An important finding of the present study is the although the subjects were working at relatively low workloads in the industrial situation (Table 7.8 and 7.9) the influence the respirator had on skin temperatures still elevated the lip temperature beyond the critical 34-34.5 °C identified by previous workers (Gwosdow *et al*, 1989; DuBois *et al*, 1990) as the temperature at which thermal discomfort is evident.

Evidence from the present study showed that the correlation between heart rate and skin temperatures (measured on the cheek and lip) when wearing the respirator, was poor to moderate (Table 7.7). The poor correlations could be accounted for by the

relatively short period of data collection (ranging from 10 - 50 minutes), or the lack of variability in some measurements. However, five of the subjects did exhibit some form of cardiorespiratory strain due to respirator use. It is concluded from the results of the study, that thermal effects played a significant part of the strain.

The results of the present study are also consistent with the laboratory study (Chapter 6) which found similar relationships between heart rate and skin temperatures whilst subjects were working at light level of exercise (50W at 60 revolutions / minute). However, mean working heart rates in the laboratory study were significantly higher than those recorded by subjects in the field study. This could be due to subjective environmental factors such as unfamiliarity with the laboratory environment and, possibly, warmer ambient environmental conditions or more likely, that they were working harder. Comparable values for cheek and lip temperatures were measured in both studies. The significance of this will be discussed in more detail in the general discussion (Chapter 8).

An interesting feature of the present study was the noticeable time delay of approximately 3 minutes, in lip temperature elevation after the respirator was placed on the subjects' face. This would likely be the time required by the facial skin thermoreceptors to initiate vasodilation<sup>\*</sup> of the nasolabial region of the face. This is supported by DuBois *et al*, (1990) who found similar increases in skin temperature under the mask within a few minutes of the subjects putting on the masks

\* (vasoconstriction is a more accurate description for this phenomenon)

In conclusion, this study of actual work activities found that:

- (i) the significant increase in heart rates in five of the twelve subjects, when respiratory protection was worn indicated cardiorespiratory strain due to respirator use,
- (ii) the respirator has a major effect of thermal conditions of the face as significant increases in lip temperatures under the respirators were recorded in all subjects when worn during work tasks,
- (iii) some general vasodilation of the face due to respirator use was evident



in four of the twelve subjects as cheek temperatures significantly increased,

- (iv) the thermosensitive areas of the nasolabial region of the face react to thermal stress within a few minutes (3) of putting the mask on.

## CHAPTER 8

### 8.0 GENERAL DISCUSSION

The principal aim of this thesis was to explore the physiological consequences of wearing respiratory protective devices and to determine the influence these consequences may have on the use of such devices. Whilst a limited number of studies have been undertaken (reviews by Raven *et al*, 1979; Louhevaara, 1984; Jones, 1991) there is a general lack of research into a number of areas. These include (i) the respirator users perceptions of comfort/discomfort, (ii) the physical characteristics of respirators and (iii) how the 'physiological cost' of wearing them may influence the perception of comfort/discomfort. This thesis draws on the results of both laboratory and field studies that have been undertaken in each of the areas outlined above.

Chapter 1 introduced a theoretical framework (Figure 1.3) upon which the measures of physiological strain could be assessed. The key physiological variables investigated in the laboratory in the present study were heart rate, oxygen consumption, carbon dioxide production and minute ventilation (see section 1.4; Chapter 4). In addition, other relevant variables including perceived difficulty breathing (Chapter 4), rated perceived exertion (Chapter 5) and facial skin temperature (Chapters 6 and 7) were also investigated. This discussion attempts to pull together the implications of the varied studies undertaken in the thesis. It identifies new information and discusses how this interrelates to existing knowledge. The chapter also discusses the limitations of the studies and qualifies the conclusions with respect to those limitations.

#### 8.1 Physiological Variables

In order to obtain some conceptual framework of the effects that respirator use has on important physiological variables it is worthwhile summarising the results of the critical studies undertaken to date. Table 8.1 attempts to provide an overview of those studies and classifies their results.

**Table 8.1. Summaries of the results of studies involving maximal and submaximal work with air-purifying devices and the effects on the variables listed. (+ + : strong increase, + :increase, =/+ :no difference or slight increase, = :no difference. =/- :no difference or slight decrease, - :decrease, - - :strong decrease).**

Variable	Effect	Submaximal*	Effect	Maximal**
Inspiratory time	+	Craig <i>et al</i> , 1970 Johnson <i>et al</i> , 1974 Stemler <i>et al</i> , 1977	+	Craig <i>et al</i> , 1970 Stemler <i>et al</i> , 1970 Johnson <i>et al</i> , 1974
Expiratory time	=/+	Gee <i>et al</i> , 1968 Craig <i>et al</i> , 1970 Johnson <i>et al</i> , 1974 Stemler <i>et al</i> , 1977 Harber <i>et al</i> , 1982	+	Craig <i>et al</i> , 1970 Stemler <i>et al</i> , 1970 Johnson <i>et al</i> , 1974
Breathing frequency	-	Gee <i>et al</i> , 1968 Hermansen <i>et al</i> , 1972 Harber <i>et al</i> , 1982 Steinhaus <i>et al</i> , 1984	-	Hermansen <i>et al</i> , 1972 Steinhaus <i>et al</i> , 1984
Tidal volume	=/+	Hermansen <i>et al</i> , 1972 Steinhaus <i>et al</i> , 1984	-	Hermansen <i>et al</i> , 1972 Steinhaus <i>et al</i> , 1984
	-	Love, 1977		
Minute Ventilation	=/-	Hermansen <i>et al</i> , 1972 Flook <i>et al</i> , 1973 Dressendorfer <i>et al</i> , 1977 Gothe <i>et al</i> , 1980 Harber <i>et al</i> , 1982 Steinhaus <i>et al</i> , 1984 Louhevaara <i>et al</i> , 1985 Babb <i>et al</i> , 1989	- -	Hermansen <i>et al</i> , 1972 Steinhaus <i>et al</i> , 1984
	=	Love <i>et al</i> , 1977 Harber <i>et al</i> , 1984 Louhevaara <i>et al</i> , 1984		
	+	White <i>et al</i> , 1975 Raven <i>et al</i> , 1979 Sackner <i>et al</i> , 1980 Jones, 1991		

**Table 8.1 - continued. Summaries of the results of studies involving maximal and submaximal work with air-purifying devices and the effects on the variables listed.** (+ + : strong increase, + :increase, =/+ :no difference or slight increase, = :no difference. =/- :no difference or slight decrease, - :decrease, - - :strong decrease)

Variable	Effect	Submaximal	Effect	Maximal
Oxygen consumption	=/+	Hermansen <i>et al</i> , 1972 Harber <i>et al</i> , 1984 Louhevaara <i>et al</i> , 1984 Jette <i>et al</i> , 1990	-	Hermansen <i>et al</i> , 1972 Lerman <i>et al</i> , 1983 Louhevaara <i>et al</i> , 1984
	-	Silverman <i>et al</i> , 1951 Thompson <i>et al</i> , 1966 Raven <i>et al</i> , 1979		
CO <sub>2</sub> production	=/-	Hermansen <i>et al</i> , 1972 Lerman <i>et al</i> , 1983 Louhevaara <i>et al</i> , 1984 Jette <i>et al</i> , 1990	-	Hermansen <i>et al</i> , 1972 Lerman <i>et al</i> , 1983
Heart rate	+	Hermansen <i>et al</i> , 1972 Dressendorfer <i>et al</i> , 1977 Lerman <i>et al</i> , 1983 James <i>et al</i> , 1984 Louhevaara <i>et al</i> , 1984 Louhevaara <i>et al</i> , 1985 Jones, 1991	=/-	Hermansen <i>et al</i> , 1972 Epstein <i>et al</i> , 1982 Lerman <i>et al</i> , 1983
	=	Thompson <i>et al</i> , 1966 Chatterjee, 1969 Epstein <i>et al</i> , 1982 Harber <i>et al</i> , 1982 Harber <i>et al</i> , 1984 Verstappen <i>et al</i> , 1986 NIOSH, 1987 Harber <i>et al</i> , 1988 Jette <i>et al</i> , 1990	=	Raven <i>et al</i> , 1977 Louhevaara <i>et al</i> 1984

\* The term 'Submaximal' used in the studies identified refers to levels of external work that range between 20 - 75% maximal oxygen uptake or an equivalent (% HRR).

\*\* The term 'Maximal' used in the studies , refers to exercise regimes that require the subjects to work to exhaustion on an elevated treadmill or cycle ergometer. The physiological criteria requires that there be no further increase in oxygen uptake despite the further increase in the level of external work.

Table 8.1 shows that the majority of the research on the physiological costs of wearing respiratory protection has been undertaken at submaximal levels of exercise (as defined in the Table). It can be seen from these studies that many of the key physiological variables (heart rate, gas exchange and patterns of breathing) remain unchanged or only slightly effected (Table 8.1). Only inspiratory time and breathing frequency are consistently modified. However, at maximal work loads (as defined in the Table), consistent effects are noted for most respiratory variables, indicating a significant effect on minute ventilation and gas exchange. In addition, changes in inspiratory and expiratory time, breathing frequency, tidal volume and minute ventilation have been most evident. Heart rate shows unaltered or conflicting responses during both maximal or submaximal levels of work.

The theoretical framework of this thesis (Figure 1.3), proposed the measurement of selected physiological parameters (measures of stress and strain) that may have been modified due to respirator use and external work. These ‘stressors’ have been either artificially exaggerated in laboratory studies, in the case of the increased breathing resistances and maintained workloads as described in Chapters 4, 5 and 6, or measured in actual field conditions (Chapter 7). Stressors that were measured or recorded in the laboratory environment included: temperature, humidity, clothing assembly, type of respirator and work demands on the individual. The experimental design adopted in Chapter 4 (Latin Square randomised block) took advantage of the power of randomised allocation of treatments that included, in addition, the opportunity of trial replication. Criticism of the technique centres around the potential for a ‘follow-on’ effect when undertaking differing levels of external work successively. In order to overcome this potential confounding factor, every effort was made to ensure that after an individual trial at a designated work load the subject had sufficient time to recover and return to a ‘steady state’ as determined by resting heart rate. In addition, the Latin Square analysis was specifically chosen as it provides a statistical mechanism of countering follow-on effects. In any analysis of variance the expected values of mean squares can be expressed in terms of components of variance that are determined by the mathematical model underlying the analysis (Munford, 1994). In the experimental design with replicate latin squares used in this thesis, the results of

the analysis of variance can be determined by examining the expected values of the mean squares for all effects and their interactions (Snedcor and Cochran, 1967; Munford, 1994). This, provided an 'effect' analysis of all measured physiological variables and their interactions. However, in order to achieve this pooled data was required. This technique removed the value of the ability of the Latin Square to control external variation on a subject by subject basis.

The physiological measures of 'strain' most easily recorded included: minute ventilation, oxygen consumption, carbon dioxide production and heart rate (Chapter 4). Skin temperature (Chapter 6) and psycho-physiological measures were also identified as important indices of strain and included perceived difficulty breathing (Chapter 4) and rated perceived exertion (Chapter 5). Parameters not recorded included inspiratory and expiratory time and deep body temperature. Breathing frequency was recorded in many, but not all, subjects in the laboratory studies by observing chest movement. Due to the difficulties of observation of chest expansion and contraction during movement in exercise this was not always possible. In retrospect, the present study would have been improved by recording  $T_i$ ,  $T_e$  and ventilation rate using a pneumotachograph and pressure transducer with a timing mechanism on a chart recorder (after Shimosaki *et al*, 1988) or alternatively using respiratory inductive plethysmography (after Hodous *et al*, 1989).

The objective of Chapter 4 was to determine whether wearing a respirator at rest and at work, imposed an additional physiological strain on an individual. A number of authors have identified changes in ventilatory pattern (minute ventilation, breathing frequency, tidal volume) as key factors in determining the physiological effects of wearing a respirator at sub-maximal levels of exercise (Dressendorfer *et al*, 1979; Harber *et al*, 1984; Louhevaara *et al*, 1984) (Table 8.1). The results presented in Chapter 4 support the general conclusions of Louhevaara (1984) that, at sub-maximal work levels, detectable physiological strain due to respirator use may be evident in some individuals but not in every case. Individual physiological responses to respirators may be highly variable and dependant on complex interrelations involving psycho-physical and social factors (Louhevaara, 1986).

### 8.1.1 Heart Rate

Evidence from the laboratory study of the physiological cost of wearing respiratory protection in 12 subjects (Chapter 4) demonstrated that at rest (5 - 11% maximal oxygen uptake) heart rate (as a measure of cardiorespiratory strain) is not affected by respirator use as determined by subject by subject analysis of variance (see Table 4.4). These results agree with earlier studies (Harber *et al*, 1984; Louhevaara *et al*, 1984) which showed that heart rate was not affected by respirator use at rest (5 - 10% maximal oxygen uptake). Louhevaara *et al*, (1984) used the same make and model of respirator (Kemira Silner 12) that was used in Chapter 4 of this thesis. The expiratory air-flow resistances of the Kemira Silner 12 was found to be the highest of those evaluated in Chapter 3 (0.2 kPa/l/sec). This value effectively doubles normal airways resistance. The dead space volume of the facemask was measured at 190 ml. Despite the presence of the respirator no significant changes in heart rate were detected within the limits of accuracy of our measurement.

When the analysis of variance was extended to all effects and their interactions for the pooled data (Figure 4.8), a treatment effect for respirator use did become significant for heart rate ( $P < 0.05$ ) at rest. These result conflict with those obtained by Harber *et al* (1984) and Louhevaara *et al*, (1984) as detailed above. The implication of this observation is that the respirator used in the experimental study (Chapter 4) imposed a physiological strain which may have been due to either increased cardiac demands of respirator use, anxiety related to dyspnea or a gradual rise in resting heart rate (Jones, 1991). The rise in resting heart rate was seen as a direct result of the increased inspiratory resistance produced by artificially occluding the inspiratory valve. As discussed in Chapter 4, the seemingly conflicting results from the statistical analysis illustrates the complex nature of the consequences of respirator use on the individual.

In addition to resting measurements, the studies in Chapter 4 of this thesis measured heart rates, with and without a respirator, in a variety of submaximal work regimens. The experimental protocol required the 12 male subjects to exercise at a level

approximately 50% of the individuals maximum oxygen uptake (range 25 - 64%  $\dot{V}O_{2\max}$ ). The latin square analysis of individual subject responses showed that, as with resting measurements, heart rate was unaffected by respirator use in all but one of the subjects assessed (n=12, age 24.5(4.8); mean (standard deviation)). As discussed in Chapter 4, these findings are significant in comparison to data collected by Louhevaara *et al*, (1985), who measured the cardiorespiratory strain in a range of selected occupations which required the regular use of respirators (relative aerobic strain for the subjects ranged from 12-70%  $\dot{V}O_{2\max}$ ). Louhevaara *et al*, (1985) found significant increases in heart rates during the heaviest work phases as a consequence of respirator use. The authors did not expand on the criteria for assessing the 'heaviest work phases' but indicated that these activities would be undertaken within the range of 50 - 70%  $\dot{V}O_{2\max}$ .

Using the same analysis of variance technique (for all effects and interactions) as used for the resting values (Table 4.8), a significant ( $P<0.001$ ) effect was demonstrated for heart rate at work (25-64%  $\dot{V}O_{2\max}$ ). However, due to the significant ( $P<0.01$ ) day by day variation in working heart rates however (Table 4.8), the results must be considered with caution.

The implications from the results obtained in Chapter 4 are that with increasing inspiratory resistance (in work situations possibly caused by clogged or blocked filters), physiological strain may occur. The effect this additional strain has on respirator wearers use the equipment may be significant if (i) the respiratory protective equipment is not well maintained and (ii) the individual is working at rest or very light (5 - 11%  $\dot{V}O_{2\max}$ ) to moderate/high (range 25 - 64%  $\dot{V}O_{2\max}$ ) levels of external work.

In Chapter 5 measurements were undertaken using a range of relatively low external levels of work (25, 50, 75 and 100W on a cycle ergometer) on subjects with and without respirators (n=7, mean age 24.9(3.9)). The study showed no clear indication of strain due to respirator use as heart rate measurements increased, decreased or were unaltered as a consequence of the experimental conditions. The subjects in Chapter



6 (n=5, mean age 37.8(6.6)) were required to maintain workloads of 50W in duplicate tests. Heart rates were shown to increase or remain unaltered as a consequence of respirator use. These results, in combination with findings from Chapter 4 and from Table 8.1, provide evidence of significant inter and intra subject variability in response to respirator use and again demonstrate the complex nature of the interaction between the device and the individual (Louhevaara, 1986).

Considered together, evidence from the laboratory based studies (Chapters 4, 5 and 6) support the view that at sub-maximal levels of work, heart rate does not appear to be generally effected by respirator use (in normal configuration). These findings are contrary to a number of studies (Hermansen *et al*, 1972; Dressendorfer *et al*, 1977; Louhevaara *et al*, 1984; Louhevaara *et al*, 1985; Jones, 1991) that found increases in heart rate over a similar range of submaximal external work regimens (using cycle ergometers or treadmills). The results obtained in Chapters 4 and 5 support previous studies (Chatterjee, 1969; Epstein *et al*, 1982; Harber *et al*, 1982, 1984, 1988; Jette *et al*, 1991) that did not demonstrate a rise in heart rate as a result of respirator use. Early studies by Chaterjee (1969) showed that the efficiency of work and corresponding physiological parameters were unaltered if workloads were low. i.e. heart rate less than 130 b/min and caloric costs of less than 6 Kcal/min (100 watts). However, it was shown that if workload was increased to 9 Kcal/min, significant decrements in work efficiency were recorded. Subsequent studies (Epstein *et al*, 1982; Harber *et al*, 1982, 1984, 1988; Jette *et al*, 1991) largely supported these initial findings. Also, as discussed in Chapter 4, explanations for a lack of cardiac response due to respirator use, could involve the age characteristics in subject groups and the ability of younger subjects to tolerate cardiorespiratory stress more effectively than older subject groups (Jones, 1988).

The field study (Chapter 7) showed evidence that heart rate was unaltered or increased as a result of respirator use in simulated and actual work conditions (n=12, mean age 35.0  $\pm$  7.2). This study, although being a compromise of methods, did provide evidence that heart rate was an important and sensitive measure of physiological strain as a result of respirator use. The relatively short durations of work monitored (10-40

minutes) were long enough for changes in heart rate to be detected in a number of subjects.

Evidence from Chapters 6 and 7 of this thesis supports a number of studies that have found that heart rates were effected by respirator use (Hermansen *et al*, 1972; Dressendorfer *et al*, 1977; Lerman *et al*, 1983; James *et al*, 1984; Louhevaara *et al*, 1984; Louhevaara *et al*, 1985; Jones, 1991). Mean heart rate data for respirator use in Chapter 6 showed a wide variability however (increase, unaltered or decrease in mean HR). As discussed previously (Chapter 7), the results of the work environment study are consistent with those obtained by Louhevaara *et al*, (1985) who showed that mean heart rate, as a measure of physiological strain in the occupations he studied, varied widely (66 to 132 b/min). Jones (1991) in a study on the physiological cost of disposable respirators found that heart rate responded in a near-linear dose-related fashion to increasing work load and that statistically significant ( $p < 0.05$ ) increases in heart rate were found with respirator use during heavy work ( $51 - 75\% \dot{V}O_{2 \max}$ ) and in subsequent recovery phases (5 min recovery/cooling off period). These results conflict with those obtained in Chapter 4, which found in general no increase in heart rate due to increased inspiratory resistance at work ( $25-64\% \dot{V}O_{2 \max}$ ).

The differing age characteristics of the subject populations in Chapter 4, 5, 6 and 7 may also contribute to the different results obtained in these respective studies. Fit, young male subjects predominantly in the laboratory studies (Chapters 4 and 5 in particular) contrasted with the older subject group (Chapter 6) and an older 'working' population (Chapter 7) subsequently investigated. My results imply the age of the subjects may influence cardio-respiratory strain due to respirator use. In addition, Louhevaara *et al*, (1985) found that interindividual comparisons are difficult because heart rate is a sensitive variable and highly dependent on each subject's physical condition.

In the study by Louhevaara *et al*, (1985), the air filtering devices used by workers were shown to cause hypoventilation, retention of carbon dioxide and a higher heart rate, during the heaviest work phases ( $50 - 70\% \dot{V}O_{2 \max}$ ). Similar cardiorespiratory

responses were not evident in all the subjects in the current study (Chapter 4). Explanations for this possibly involve the differing types of work activity observed by Louhevaara *et al.*, (1985) in his study (construction, demolition, foundry, welding and shipyard work). These activities are commonly thought of as heavy and physically demanding, with oxygen consumption values between 25 - 80%  $\dot{V}O_{2\max}$  and heart rates ranging from 90 - 150 b/min. However, in all probability, the activities would be intermittent, as work load is likely to vary on a minute by minute basis. How well continuous work on a cycle ergometer simulates the work that occurs in the industrial environment must remain a matter of some conjecture (Astrand and Rodahl, 1986).

It is concluded that the use of respiratory protection in the laboratory studies (Chapters 4, 5 and 6) and in the work environment study (Chapter 7) did impose cardiorespiratory strain during submaximal levels of work, as measured by increases in mean heart rates in many, if not all, individuals. When inspiratory resistance was artificially increased (Chapter 4), physiological strain may become more evident.

### 8.1.2 Gas Exchange

Evidence from the Latin square analysis of the results from Chapter 4 showed that wearing a respirator at rest (5 - 11 %  $\dot{V}O_{2\max}$ ) and during submaximal levels of work (25 - 64%  $\dot{V}O_{2\max}$ ) compromised oxygen consumption and carbon dioxide production in only two of the twelve subjects. The respiratory exchange ratio was not effected. Oxygen consumption has been shown to remain unaltered, slightly increased or decreased at submaximal (20 - 70%  $\dot{V}O_{2\max}$ ) levels of work when wearing respiratory protection (Table 8.1) (Hermansen *et al.*, 1972; Harber *et al.*, 1984; Louhevaara *et al.*, 1984; Jette *et al.*, 1990) but decreased on maximal exertion (Hermansen *et al.*, 1972; Lerman *et al.*, 1983; Louhevaara *et al.*, 1984). My results from this analysis were consistent with the previous studies (Hermansen *et al.*, 1972; Harber *et al.*, 1984; Louhevaara *et al.*, 1984; Jette *et al.*, 1990), which demonstrated that the use of air-purifying respirators imposed no significant increases in workload (as measured by changes in oxygen consumption) on individuals required to wear them during submaximal exercise regimens.

The effect of wearing a respirator with impeded inspiratory resistance on gas exchange at work (25 - 64%  $\dot{V}O_{2\max}$ ) (Chapter 4) demonstrated a significant ( $P < 0.05$ ) increase in carbon dioxide production when analysis of variance of the pooled data was considered. As discussed in that Chapter, the results are enigmatic due to the considerable day to day variation in minute ventilation measured during the experimental trials (Table 4.8) and the unchanged values of the respiratory exchange ratios. However, the results agree with earlier studies using self contained breathing apparatus and air-line breathing equipment (Raven *et al*, 1977; Louhevaara *et al*, 1984; Steinhaus *et al*, 1984; Louhevaara *et al*, 1985) that reported similar results. The results of these studies identified significant changes in gas exchange, heart rate and physical work performance due to the use of these devices. However, my results were contrary to previous studies of air-purifying respirators where carbon dioxide production has been shown to remain unchanged or slightly decreased at submaximal and maximal levels of external work (Hermansen *et al*, 1972; Lerman *et al*, 1983; Louhevaara *et al*, 1984). As oxygen consumption was shown to remain unchanged (Table 4.8) the findings tend to indicate that the subjects were hyperventilating as a consequence of respirator use, particularly when the subjects were at work and when the modified respirator was worn (artificially increased inspiratory resistance).

Raven *et al*, (1979) reviewed a number of studies that demonstrated that only at high work rates (70-80%  $\dot{V}O_{2\max}$ ) where breathing frequency was reduced by 30-45% was oxygen consumption compromised (Hermansen *et al*, 1972; Dressendorfer *et al*, 1977; Louhevaara *et al*, 1984). Increased expiratory resistance has been shown to produce a decrease in the frequency of breathing (Tabakin and Hanson, 1960; Levy, 1991). This in turn leads to a reduction in oxygen consumption and carbon dioxide production i.e. hypoventilation (Gee *et al*, 1968). It was unfortunate that breathing frequency was not consistently measured in this study. However, at the levels of external work imposed on subjects in the present study (25 - 64%  $\dot{V}O_{2\max}$ ) it is arguable, based on the review by Raven *et al* (1979), whether any detectable change in oxygen consumption due to changes in minute ventilation would become evident.

It is concluded that the physical characteristics of the respirator in its' normal

configuration (air resistance, dead space and weight) used in the experimental study (Chapter 4) did not significantly (to our limits of accuracy) effect gas exchange in subjects, during submaximal levels of external work. There was, however, a measurable change in gas exchange (carbon dioxide production) as a result of artificially increasing the inspiratory resistance of the respirator. The physiological significance of this is unclear, although it is possible that the findings demonstrate that the subjects were hyperventilating (increased carbon dioxide production) during the later stages of the exercise protocol. These results, indicating that an increase inspiratory resistance (possibly caused by a failure to change a 'clogged' filter), may have important consequences in the work environment.

### 8.1.3 Pattern of Breathing

Any respirator increases the external dead space of the respiratory system. The addition of dead space has been shown in many instances to increase minute ventilation (Stannard *et al*, 1948; White *et al*, 1975; Raven *et al*, 1979; Sackner *et al*, 1980). The measurements undertaken in Chapter 3 indicate that an air-purifying respirator approximately doubles the normal anatomical dead space of an individual. However, the results in Chapter 4, revealed no corresponding alteration in minute ventilation in respirator users at rest or at moderate levels of external work. The range of dead space volumes measured in the present study (150-220 ml) could be considered small in comparison to other respiratory devices where large dead space volumes (up 1000 ml) may have produced significant strain on wearers (Louhevaara, 1984). Both published evidence (Louhevaara, 1984; Jones, 1991) and my study suggest that dead space volumes of less than 200ml do not produce noticeable changes in breathing particularly at sub-maximal levels of work. This observation may be significant for designers and manufacturers of the equipment. Respirators with dead space volumes much in excess of 200ml were not evaluated in the present study. Further study contrasting the effects of respirators with large and small dead space volumes might provide useful information on changes to gas exchange and breathing patterns induced by additional dead space imposed by some respirators.

Conversely, as Jones (1991) commented in his review, many studies have shown a decreased minute ventilation with air-purifying respirator use (Flook and Kelman 1973; Dressendorfer *et al*, 1977; Gothe *et al*, 1980; Harper *et al*, 1982; Louhevaara *et al*, 1985; Babb *et al*, 1989). Yet other studies have shown no effect on minute ventilation (Love *et al*, 1977; Harber *et al*, 1984; Louhevaara *et al*, 1984). The evidence from the present study suggests no changes to minute ventilation occur even up to exercise levels of 50% maximal oxygen uptake. Alternatively, any changes that did occur were beyond the accuracy and precision of the equipment used in the methodology. As an example, of the measurement equipment utilised in the experimental studies, the heart rate monitor and dry gas meter had tolerances of between 1 and 2 percent, with the Datex Normocap gas analyzer accurate to within 3 percent (refer section 4.2.2). Thus with a standard error of measurement in the order of 1, 2 and 3% there is some confidence that any significant changes in the physiological variables would have been apparent using this equipment.

Initial survey investigations (Chapter 2) indicated that respirator weight was important to perceptions of user discomfort, although secondary to thermal sensations (by ranking order). Further, that study revealed that respirator users had clear preferences for lightweight, comfortable but effective protection against air-borne contaminants. It was not possible in the present study (Chapter 4), however, to show changes to patterns of breathing (minute ventilation), gas exchange or heart rate were directly attributable to the weight of the device. The respirator used not only had the highest expiratory and inspiratory resistances of all those evaluated but, also, was the heaviest respirator (Kemira Silner 12). Further research would be useful in determining the relative effect that respirator weight has on individual performance, particularly with the use of air-purifying devices.

An awareness of the individual's breathing and breathing pattern also was identified (Chapters 2 and 5) as an important factor in respirator tolerance. The subjects' awareness of the respirator valves 'flapping' during inhalation and exhalation also create a heightened subjective responses to the presence of the respirator. This valve phenomenon was first recorded by Cotes (1962) who observed on the 1953 British

Mount Everest Expedition that the inspired valve opening pressure produced a large degree of subjective discomfort, especially if the valve was wet.

Other relevant factors that were identified in this thesis that contributed to situations of respirator non-use were psychosocial influences. In recent work undertaken in New Zealand on psychosocial influences to respirator non-use, Clark (1992) found that apart from the physical discomfort of the device, more general factors were of concern to users. These included feelings of claustrophobia and having an awareness of one's breathing. Clark (1992), cites the example of one respondent commenting:

" it's mentally irritating, in your head, actually hearing yourself breathe."

In addition, problems with interpersonal communications, difficulties with seeing adequately and moving and feeling self conscious and awkward were prominent reasons for non-use of the equipment.

The study by Clark (1992) found that respirator users tolerated the annoying and uncomfortable effects of using the respirator by developing strategies for managing the disadvantages of use. These strategies involved (i) modifying work regimens by altering work-schedules, (ii) alternating jobs and (iii) developing more efficient work methods. Clark (1992) found rest breaks to be a common way of handling the discomfort of wearing a respirator and that workers co-operate with each other to manage these breaks.

It is concluded that the inter-relation between increased expiratory and inspiratory air-flow resistance, increased external dead space and weight in respirator use is complex and a number of physiological variables may be affected. An individual's response to one condition (e.g increased dead space leading to an increase or decrease in minute ventilation) may be counteracted by the response to another (e.g. increased resistance leading to an increase or decrease in minute ventilation). The 'net' effect would be little detectable change in the physiological variable.

**Table 8.2. The range of mean facial skin temperatures (lip temperatures) measured in the laboratory and field studies, with and without wearing respiratory protection.**

Laboratory Studies	Field Study
with respirator 31.5 - 36.7°C	with respirator 30.1 - 35.9°C
without respirator 28.7 - 36.4°C	without respirator 28.4 - 34.0°C

**Table 8.3. The range of mean facial skin temperatures (cheek temperatures) measured in the laboratory and field studies, with and without wearing respiratory protection.**

Laboratory Studies	Field Study
with respirator 29.6 - 35.3°C	with respirator 28.7 - 34.6°C
without respirator 28.4 - 34.6°C	without respirator 28.4 - 33.1°C

The Tables (Tables 8.2 and 8.3) confirm that a small relative increase in mean skin temperature occurs during respirator use and that the critical temperature range for discomfort (34 -35°C), suggested by DuBois *et al*, (1990), occurs in a number of cases. The Tables also illustrate a close correlation between laboratory and field measurements.



#### 8.1.4 Facial Skin Temperature

Studies conducted in this thesis (Chapters 6 and 7), on the effects respirator use has on facial skin temperatures, have found small (mean  $1.5(0.3)^{\circ}\text{C}$  from Chapter 6 and mean  $2.3(0.7)^{\circ}\text{C}$  from Chapter 7) increases in facial skin temperature under the respirator mask ( $T_{\text{lip}}$ ). A temperature rise was also recorded on the cheek ( $T_c$ ), indicating some general facial vasodilation may have occurred. These temperature increases were perceived by the subjects wearing respirators who reported sensations of thermal discomfort during and after the exercise period. The range of facial skin temperature increases between the laboratory and field study are summarised in Tables 8.2 and 8.3.

These results agree with those of DuBois *et al.*, (1990), who found that the critical skin temperature range for sensations of discomfort is between  $34 - 35^{\circ}\text{C}$ . DuBois *et al.* (1990) showed an increase in mean facial skin temperature (lip) from a control of  $33.4^{\circ}\text{C}$  (s.d. 0.52) to  $34.9^{\circ}\text{C}$  (s.d. 0.36) after 30 minutes of wearing a respirator mask. In addition, these authors found similar values for a porous dust-mask type respirator that were between  $33.8^{\circ}\text{C}$  (s.d. 0.64) to  $35.9^{\circ}\text{C}$  (s.d. 0.54) after 30 minutes. Measurements for an aluminium mask cooled by wetting were virtually unchanged after 30 minutes ( $34.0\text{-}34.1^{\circ}\text{C}$ ). It was found that masks were perceived as comfortable when the skin temperature of the face was  $33^{\circ}\text{C}$  and became slightly uncomfortable at a skin temperature of  $35^{\circ}\text{C}$ . Sensations of discomfort were reported in the present study by subjects with skin temperatures below or approaching these values. The data also provided evidence that very small changes in facial skin temperature are detected by respirator users and that this is an important cue for feelings of discomfort.

The implication is that whatever the mechanism may be, thermal sensations of the skin play an important role in the physiological and psycho-physiological or comfort aspects of respirator use or non-use. DuBois *et al.*, (1990) comment that discomfort may be related to thermal sensation, sweating and hydration, condensation of expired alveolar water vapour, cutaneous bloodflow, or vascular congestion, or all of the above.

## 8.2 Limitations of the Experimental Studies

### (i) Duration of experimental trials

An important factor of a general nature to this thesis was the comparative lengths of time that the subjects were working in the experimental studies. These were typically between 5 - 30 minutes in the laboratory studies (Chapters 4, 5 and 6) and between 10 - 50 minutes in the field study (Chapter 7). Whilst many earlier studies (reviews by Raven *et al*, 1979; Louhevaara, 1984; Jones, 1991) used experimental protocols with similar times for data collection (5 - 30 minutes). I could find no studies that have been published that attempted to measure physiological responses due to respirator use in excess of 30 minutes. The results of the respirator use survey, however, (Chapter 2) clearly indicate that a large proportion of respirator users wear the equipment in excess of 1 hour (and many for over 4 hours) each day. Further research would be useful in determining the effect that extended respirator use (in excess of 1 hour) has on the identified physiological variables. The further use of the SAMI's (Chapter 7) in work situations would provide useful data on the effects of respiratory protection during use over extended time periods.

### (ii) Accuracy and Precision of Experimental Measurement

It is important to consider whether an absence of demonstrable change in many of the physiological variables examined in this study is the result of a lack of sensitivity of measurement in the experimental procedures. The experimental procedures adopted in the thesis were designed to be rigorous enough to limit external sources of variation. In addition, as discussed earlier, the tolerance limits of the experimental equipment employed were found to be sensitive enough, in terms of accuracy and precision (1 - 3 percent), to provide data with acceptable standard errors (refer Materials, Methods and Equipment sections). Given these limitations it is concluded that the results recorded are valid measurements of physiological variable responses within the detection limits of the equipment. It is improbable that any individual would be aware in a change of less than 3 percent in any of the variables measured except, possibly, skin temperature.

### 8.3 Psycho-physiological Responses to Respirator Use

Relatively few studies have measured subjective responses to respirator use, even though the rationale for including perceptual variables as a complement to physiological variables has been well established and confirmed for over thirty years (Borg and Dahlstrom, 1962). Studies on psycho-physiological responses to respirators have primarily used visual analogue scales to provide quantitative, subjective information (Epstein *et al*, 1982; Morgan, 1983; Morgan and Raven, 1985; Manninen *et al*, 1988; Shimozaiki *et al*, 1988; Harber *et al*, 1989; White *et al*, 1989; Wilson *et al*, 1989; Jette *et al*, 1990; Harber *et al*, 1991). The importance of including subjective measures of exertion or respiratory distress became evident in the survey of use and non-use of respirators (Chapter 2). The study indicated there were definite psycho-physiological and psychological reasons for non-use in terms of difficulty in breathing, difficulty doing the job or feeling awkward or self-conscious. In addition, approximately 30% of the respirator users (or non-users) surveyed indicated that they considered their workloads were physically hard. This was contrary to the results of the Work Environment studies (Chapter 7) which demonstrated that the range of heart rates measured during actual work activities could be considered light to moderate (Astrand and Rodahl, 1977; Louhevaara *et al*, 1985).

Perceived difficulty breathing or breathlessness, is an important psycho-physiological measure in respiratory medicine and physiology. Comroe (1966) defined difficult, laboured or uncomfortable breathing as *dyspnoea*. According to Astrand and Rodahl (1977), the reasons why respiration may become consciously troublesome is unclear. Cameron and Bateman (1983) suggested the terminology can become confusing in the clinical sense, since two separate sensations may be involved: Firstly, 'shortness of breath' - the sensation which accompanies an increased ventilation, usually accompanying exercise or, secondly, if the airways are narrowed and the need for ventilation is made difficult by an increase in airway resistance. Hence, the term *dyspnoea*, may be used to describe different sensations arising as a consequence of different mechanisms. Another, more useful definition, defines *dyspnoea* as an increased sense of respiratory effort (Killian, 1985). However, it may be argued that

this definition is limited as it does not take into account the psychological causes of sensations of dyspnoea.

In the present study the feeling of breathlessness due to the effects of the submaximal exercise regime, linked to the 'additional' external resistance imposed by the respirator, was most effectively evaluated using the 'perceived difficulty breathing' scale. The perceived difficulty breathing scale was developed by Morgan and Raven (1985) and these authors used it in the assessment of respiratory distress whilst undertaking submaximal exercise tests and wearing respiratory protective devices (SCBA). The measures of distress were correlated with standardised psychological inventories designed to measure an individual's proneness to experience distress. The rationale for their study came from the common observation that certain "types" of individuals experience breathing distress or "claustrophobia" while wearing respirators and this could explain why certain individuals remove or decline to use respirators while working in contaminated environments e.g. firefighters removing their masks while fighting a fire (Morgan, 1983).

The experimental conditions imposed on the subjects in Chapter 4, i.e submaximal exercise regime when wearing (i) no respirator, (ii) a respirator in a normal configuration and (iii) a respirator with an artificially increased inspiratory load, provided clear evidence of the incongruence between the physiological and subjective measures of distress. That is, in the absence of measurable physiological responses (alterations in oxygen consumption and minute ventilation) in subjects working at moderate levels of work ( $25 - 64\% \dot{V}O_{2\max}$ ) (Chapter 4 and 5) there were significant ( $P < 0.05$ ) increases in perceived difficulty breathing (PDB) (Chapter 4) and rated perceived exertion (RPE) (Chapter 5). These results are in agreement with previous studies (Morgan and Raven, 1985; Shimosaki *et al*, 1988; Harber *et al*, 1989), that demonstrated increases in psychological ratings of distress during respirator use with no corresponding changes to in cardiorespiratory strain (as measured by heart rate, gas exchange and pattern of breathing), but differ from other reports (Harber *et al*, 1991; Jette *et al*, 1991), who found no significant subjective differences between various types of air-purifying respirators.

'Perceived difficulty breathing' appears an obvious, but relatively unresearched and under-utilised measure of respiratory distress, that could be effectively used by individuals in industry charged with the responsibility of assessing and prescribing respiratory protection required in the work environment. The use of the scale is said to be relatively free from bias or misinterpretation (Morgan and Raven, 1985) and would provide a sensitive tool to complement other physiological measures. However, it is apparent from the results of the survey of respirator use and non-use (Chapter 2), that in most of those industries surveyed, detailed medical or physiological evaluations of the user are not undertaken prior to the respirator being issued. Raven *et al*, (1981, 1985), suggested the need for a simple clinical test which could be used as a means to screen industrial workers as to their capacity to wear a respirator. Subsequently, a number of pulmonary function tests have been proposed as predictors of work performance during respirator use (Freedman, 1970; Raven *et al*, 1981; Wilson and Raven, 1989). These include maximum voluntary ventilation in 15 sec ( $MVV_{.25}$ ), forced vital capacity (FVC), forced expiratory volume in 1 sec ( $FEV_{1.0}$ ) and peak inspiratory flow ( $PF_I$ ). These authors propose that by measuring the  $MVV_{.25}$ , calculating potential reduction caused by respirator use and combining this information with the required ventilation of the work task, the evaluator (physician) will be able to determine each worker's ability to work while wearing a respirator, regardless of the presence of pulmonary disease. This statement however, whilst technically valid, ignores the complex psychological component of the person-respirator interface. In his review of psychological problems associated with the wearing of industrial respirators, Morgan (1983) suggests that the absence of systematic research in the area should not be interpreted to mean that the problems have not been recognised, but that psychometric diagnostic 'tools' to identify individuals likely to 'hyper-respond' while wearing respirators have not been developed.

In order to determine an individual's ability to work while wearing a respirator as suggested by Wilson *et al*, (1989), the evaluator would require a fairly accurate estimate of the resistances of the respiratory devices to be used, in addition to the energy and ventilatory requirements of the job the worker will be engaged in and the probable length of time the respirator will be worn. It is clear from the evidence of

my study (Chapter 2) that respirators were worn by many (30% of respondents) at work for considerable lengths of time (in excess 1 to 4 or more hours per day).

At this point two comments can be made: Firstly, what is the practicality of obtaining this information and secondly, most, if not all, users of industrial respirators will be working at submaximal levels of work, where it has been shown that respirator use has a variable (decreased, increased or unaltered) effect on ventilation rates and volumes (White *et al*, 1975; Love *et al*, 1977; Raven *et al*, 1979; Harber *et al*, 1984; Louhevaara and Tuomi, 1984; Louhevaara *et al*, 1985). These two points when considered together, support the view that the physiological prediction of wearer suitability is not only impractical but also of not much value. Procedures which place an emphasis on physiological parameters centre around the 'objective' measure or prediction of distress and generally ignore individual wearer's perceptions and beliefs.

This view is also supported by results from the survey of respirator use (Chapter 2), in which respirator users from the South Island site reported perceived difficulty breathing as a subordinate reason for non-use (ranked 5th in terms of frequency), even though they were working in an environment that was physically stressful (20-30°C Td, 23-26°C Tw) and demanding (moderate to heavy levels of external work). In this case, however, the use of respiratory protection with low inspiratory and expiratory resistances was possibly an important factor in the responses. The respirator most commonly used at the South Island site was the Sundstrom SR 90. This model was shown to have the lowest resistance of all the air-purifying devices with cartridges available in New Zealand and tested in the present study (expiratory and inspiratory resistance of 0.09 kPa/l/sec) (Chapter 3) and was similar in air-flow performance to a porous dust-mask type respirator (refer Chapter 3, section 3.4). The dust-mask type respirators were often tolerated better than air-purifying models with cartridges (Chapter 2).

Another psycho-physiological factor used in this thesis was Rated Perceived Exertion (RPE) (Chapter 5). Even though the validity of using the RPE scale is well established (see Fleishman *et al*, 1984; Goslin and Rourke, 1986; Ljunggren, 1986 for

reviews), the incongruence between physiological and perceptual measures of distress when wearing respiratory protection were again clearly demonstrated. At the light to moderate work levels used in the study (50-100W on a cycle ergometer), relative absolute differences in RPE values with respirator use ranged from 0.80 at 50 and 75W, to 1.25 at 100W external workload and represented approximately an 8-10% increase in perceived exertion. This increase was detected with no significant or comparable increase in cardiorespiratory response i.e. heart rate. Some, or all of the factors discussed in this section may play an important role in the users reasons for use and non use. The compelling question is which combination of physical, psychological, physiological and social factors lead to respirator non-use.

#### 8.4 Surveys of Respirator Use and Non-Use

The results of the surveys of use and non-use in workplaces in New Zealand (Chapter 2) provide evidence that non-use is, in fact, quite common. The survey of the Palmerston North and Horowhenua area was useful as it provided a cross section of a variety of industries and occupational groups. It confirmed that air-purifying respirators are the most common form used in the workplace and that protection from exposure to dusts, mists and vapours constitute the major reason for their use. The present study provided new information in two respects. Firstly, no previous comprehensive studies have been undertaken to determine the nature and extent of exposure to contaminants in these regions of New Zealand. Secondly, the present study was the first in New Zealand, to survey the extent of respirator non-use in industry. The results provide evidence that the use of personal protective equipment in local industry was still common but that the protection afforded by the devices are compromised by the high percentage of non-use. The legal and medical implications of these findings may be significant.

The survey of the South Island manufacturing site provided evidence that respirator non-use was also a common practice among those required to wear them by management. This finding was significant as The Occupational Health Service of the organisation has a comprehensive information and training programme for respiratory

protection and staff are employed solely to monitor and maintain this service.

Another significant feature of these results was that nearly 30% of all those surveyed that wear respiratory protection considered their workload strenuous or physically hard and that air-purifying respirators are worn for considerable lengths of time i.e. between 1 and 4 hours or more (Chapter 2). However, it was clear from the results of the Work Environment Study (Chapter 7), that these perceptions of exertion were not supported from physiological measures obtained in the workplace (mean heart rate values ranged from 70-95 beats per minute). Ljunggren (1986) obtained similar results indicating overestimations of perceptions of exertion (RPE) in a study with subjects working on a cycle ergometer.

Over 50% of respondents in both surveys said they removed the respirator for a variety of reasons before the work that required its use was completed. The most frequent reasons for removal reported by users, were those of thermal discomfort, followed by difficulty in seeing, breathing and communicating. In addition, a significant number of respondents indicated that they had difficulty completing the task, which indicated that the respirator was an intolerable hinderance to their work. The results of the present study confirm earlier research that reported similar reasons for respirator non-compliance (Anon, 1970; Harris, 1974; Aucoin, 1977; National Coal Board, 1977).

Feeling awkward or self-conscious when wearing the devices was of concern to over 10% of all respondents. This finding emphasises the importance of psychosocial factors in protective equipment non-use. A small number of respondents (10% of all respondents) also gave detailed descriptions of the symptoms of exposure they had experienced including headaches, nausea, dizziness, breathing difficulty and fatigue. A large proportion of those responding to the survey indicated they received little or no information on the use and maintenance of the equipment (although this was not the case with the South Island respondents).

Personal experience is widely believed to have a substantial impact on the recognition



of risk. Previously published research findings suggest that personal experience generally increases feelings of susceptibility and worry and increases the saliency of the risk, although it may either increase or decrease perceived seriousness, depending on the type of experience or situation (Weinstein, 1989).

There appeared to be differences in the factors which individuals use to determine and separate acute, immediate hazards from long-term (delayed-effect) hazards (Green and Brown, 1978). This was evident from the usage survey (Chapter 2, sections 2.3.1 and 2.4) where, depending on the nature of the contaminant, almost 40% of respirator users surveyed perceived the long term effects of exposure as the most hazardous to health. However, delayed-effect hazards tend to be seen as unfamiliar and less controllable than acute hazards (Green and Brown, 1978) and familiar hazards are more tolerated than new or strange risks (Weinstein, 1989). When given a choice, individuals tend to accept higher voluntary risk levels than if the same risk were imposed by others (Phillely, 1991). Controllability of the risk of injury or harm appears to be a major component in an individuals assessment of specific hazards (Hale and Glendon, 1987). Factors, such as the freedom to choose whether or not to expose oneself to the dangers of the activity, the degree of trust in people in control, the benefits arising from the activity and who stands to gain from the activity, may all be important (Hale and Glendon, 1987). Evidence from the present study (Chapter 2) demonstrated that many respirator users perceive little benefit from wearing the equipment and that respirators may even hinder work operations. Reasons for non-use were far more frequently reported than reasons for use (Chapter 2, section 2.3) the fact that work related tasks were more difficult to accomplish when wearing the respirator (Chapter 2, section 2.3.2) was a major reason for non-use.

A study by White *et al*, (1988) looked at the factors which may influence the frequency of use of respiratory equipment and specifically considered the role of personal beliefs and social influences. Results of this study of 169 male construction painters indicated that painters who reported low use of respirators were significantly more likely to have beliefs that the respirator would be uncomfortable, would get in the way, would cause difficulty breathing and would make the user feel closed in.

These individuals were also less likely to agree with statements concerning various health benefits of use, such as feeling more mentally alert, living longer, having less risk of cancer and being able to produce healthy children, than painters reporting high use. Painters who wore respirators less frequently were significantly more likely to agree that other people would think that they were foolish. Respirator availability, however, was associated with respirator use. The study suggested that if systems were in place for workers to have ready access to a range of equipment and if information and support was available for maintenance of the equipment, then it was more likely that there would be higher rates of respirator use. Based on current evidence from the North Island and South Island surveys of respirator use (Chapter 2), this assumption could not be supported. A more comprehensive programme was in place for instruction in respirator use, a larger range of equipment was available and far greater support to workers was offered in the South Island plant compared with any other operations in New Zealand industry with which the author is familiar. Nevertheless, the compliance with the requirement to wear respiratory protection was no better in the South Island plant compared with the general industries of the North Island survey. However, this finding must be qualified by the relative lengths of time that the respirators were worn within each study group (20% of the PN respondents and 42% of the South Island respondents wore respirators in excess of 4 hours per day).

An early study by Pirani and Reynolds (1976) revealed that although individual workers themselves thought that a safety conscious person who wore protective equipment was sensible, they believed that other workers would see him as a "cissy" and respect him less. The present study (Chapter 2, section 2.4) provides evidence that a number of respirator users (10%) felt self-conscious and awkward when having to wear a respirator and that these feelings had a direct impact on respirator use. Wogalter, Allison and McKenna (1989) also looked at the role of social influence on people's use of protective equipment and found that the behaviour of one's peers has an influence on compliance with warnings.

The other major reason for respirator non-use reported by Palmerston North users was difficulty in breathing. This was not evident to the same extent in the South Island

survey and was ranked fifth in importance as a reason for non-use. This evidence is consistent with the differing air-flow resistances measured for the various types of respirators used in the locations and reported in Chapter 3. The significance of these findings is important as the measured resistances of all the devices tested in the present study were low in relation to International Standards (Australian Standard 1716, 1991). The results from Chapter 3 also provided evidence that the number of exhalation valves in the facemask had a significant effect on measured expiratory resistances (Figures 3.1 and 3.2). Those devices with twin exhalation valves appeared to have a more efficient mechanism of venting exhaled air than the single valve devices. The finding has implications for design and manufacturers of respiratory protective equipment and also for respirator wearer's in the selection and maintenance of the devices.

One criticism that could be made of the surveys undertaken is the subjective nature of the data (Babbie, 1973) and the lack of objective measures used to validate the responses (Dixon and Massey, 1969). A number of authors with knowledge of the area would dispute these criticisms on the basis that respirator users subjective responses to wearing the equipment are of equal importance to objective measures of stress and strain (Beckett and Billings, 1985; White *et al*, 1989; DuBois *et al*, 1990). In addition, the surveys cannot be considered in isolation to other sections of the thesis, where objective measures of strain were examined.

Relationships between the implementation of environmental control technologies and usage data for personal protection such as those discussed here are important in any evaluation of associated industrial health and safety issues. Whilst compiling the database from which to select the industries and premises suitable for this study, it was apparent that in many industries the dependence on the use of respiratory protective equipment has been reduced in recent years by the introduction of environmental control techniques (Safeguard, 1992). As a result, workers no longer need to wear personal protection in many instances. This move toward better occupational hygiene practice may be attributable to the implementation of a variety of Codes of Practice in New Zealand industry (Safeguard, 1992). Many activities

traditionally requiring extensive use of respirators have been significantly modified. This has resulted in a reduction in the number of respirator users in a number of industries. However, there exist many work activities e.g spraying agricultural chemicals, where environmental control technologies are difficult to implement or impracticable. In these situations there is still a reliance on 'individual factors' for protection and safety attitudes, perceptions and behaviour are important factors in ensuring individuals use and wear appropriate personal protective equipment.

### 8.5 Studies of the physical characteristics of respiratory protective equipment.

As Louhevaara (1986) commented: - "the industrial respirator is a complex device". They may interfere with sensory functions such as hearing and vision and impede speech and movement. They may be incompatible with corrective lenses or other protective equipment. Their efficiency may be reduced due to facial hair preventing an adequate seal. However, discomfort is perhaps the most important aspect for the wearer. Respirators can be heavy, hot, tight, may irritate the skin and cause an accumulation of sweat (Morgan, 1983; Terrell, 1984). The wearer may experience difficulty breathing, anxiety or claustrophobia and the presence of some pre-existing health conditions may make the use of some respirators difficult (Raven *et al*, 1979; Louhevaara, 1984; Jones, 1991).

Chapter 3 examined three quantifiable variables, air-flow resistance, the volume of dead space and weights of the devices. Evaluations of air flow resistances of respirators commonly used in New Zealand industry (Chapter 3) indicate that most have relatively low inspiratory and expiratory resistances and are well within the International and New Zealand Standards (Australian Standards Association, 1991). The dead space volumes of the facemasks were found to be similar (150-220ml), given the varying designs and valve configurations. This is in contrast to earlier studies (see reviews by Raven *et al*, 1979; Louhevaara, 1984) who found dead space measurements ranging from 195-500 ml for air-purifying equipment and up to 1000 ml for some air-supplied devices. The weights however, varied considerably.

In Australia and New Zealand, one standard (AS 1716 - 1991 Respiratory Protection Devices, Australian Standards Association) is used to evaluate the relative performance of respirators. The standard requires that inhalation resistance is measured at two different continuous air flow rates with a filter mounted on the mask. At 30 l/min the pressure drop must not exceed 1.2 mbar, while at 95 l/min the drop must not exceed 3.7 mbar. Exhalation resistance is only measured at 85 l/min and should not exceed 1.2 mbar. Measurements of inspiratory and expiratory resistances in Chapter 3 (table 3.6) indicated that the all of respirators evaluated were within the criteria specified in the standard. However, as one article (Safeguard, April 1992) commented: - "standards approval says little about performance, wearability, comfort and efficiency of breathing protection. Standards testing procedures may not reflect the use of the product in actual work situations and, even if normally adequate, the standards requirements may not be appropriate for some workers". One respirator manufacturer (Sundstrom) has suggested that the Standards test criteria are, in the case of inhalation, unrealistic and in the case of exhalation, insufficient. The Australian Standard should only be regarded as a reference value, the company says and was never supposed to be anything but a 'minimum requirement', with the emphasis on quality control and performance consistency. It was demonstrated in Chapter 3 that the inhalation and exhalation resistances of the respirators evaluated were within the standard requirements (1 mbar=102 Pa, range of resistances 0.04-1.0 mbar at 85 l/min).

The significance of the results from the present study (Chapter 3) become evident when the physiological and psycho-physiological data (from studies in Chapters 4,5 and 6) is related to the measurements of resistance. In doing so, it becomes clear that even with the demonstrated low inspiratory and expiratory resistances (range from 0.01 - 0.2 kPa/l/sec) perceptions of exertion, difficulty breathing and thermal discomfort were the variables most effected ( $P>0.05$ ) during the experimental studies. These findings in combination with the evidence provided by respirator users in industry (Chapter 2) lead to the conclusion that perceptual and sensory factors may be the more dominant 'triggers or cues' for respirator non-use than physiological measures of strain (heart rate, gas exchange and minute ventilation).

The history of the development of resistance standards for respirators is one of complex scientific and political debate. Love (1981) suggested that standards for inspiratory and expiratory levels of resistance of many different kinds of apparatus are far from being universally agreed. Inter-country comparisons are also complicated by the fact that resistances may be measured and expressed at different airflows, which cannot be directly compared with other values in the literature owing to the non-linear nature of most resistances. The work of Silverman *et al*, (1943 and 1945) and Cooper (1960) is widely quoted as the basis for many of the current standards of breathing resistance. Maximum levels of inspiratory flow resistance for respirators used by subjects at rest and under varying conditions of exercise have also been suggested by Cotes (1962). However, most standards currently used today require resistance measurements using *continuous* monodirectional air flow. This seems incongruous as the studies undertaken by Silverman *et al*, (1943, 1945) used mean air flow curves (reciprocating flows) plus twice the standard deviation to: - "aid in the design of canisters, pumps and testing apparatus for simulating the actual conditions". The authors suggested that the airflow curves would be useful for design specifications of respirators and that reciprocating flows were preferable to continuous flows for this purpose. In a later study, Silverman *et al*, (1951) suggested that such information was of value in the design of protective respiratory equipment such as gas masks, dust masks and oxygen supply equipment for aviators.

Cooper, (1960), specifically suggested that:- " the recording of pressure-volume diagrams for breathing apparatus when ventilating by a sine-wave pump will give valid estimates of the external respiratory work which would be done by a wearer in practice and that these estimates would offer a useful means of comparison of various breathing apparatus". The application of these principles to the evaluation of the respirators in Chapter 3, indicated that the pressure-volume relationships for cartridge and dust-mask types of respirators (Appendix 4 Figs. 3.1 - 3.8) provided little additional information that would be of significance to respirator designers. Whilst it was interesting to measure the dynamic characteristics of the airflows during the inspiratory/expiratory cycle, the pressure fluctuations that were identified were due either to the air purifying mechanism (activated charcoal or adsorbent material) or the

valve mechanisms (if incorporated).

A feature that was identified in the present study was the detectable pressure fluctuation that occurred at the peak of the inspiratory/expiratory cycle (Appendix 4 Figs. 3.6, 3.7 and 3.8). This was likely to have been due to the operation of the expiratory valve system of the respirator face mask. The Protector and Kemira respirators (Appendix 4 Figs. 3.6, 3.7 and 3.8) showed this feature most clearly, whereas the disposable face masks did not demonstrate it (Appendix 4 Figs. 3.1 and 3.2) owing to the absence of expiratory and inspiratory valves in the devices. This is significant as the perception of pressure fluctuations by an individual due to the expiratory or inspiratory valve opening and closing was identified by Cotes (1962) as one of the more unpleasant consequences of respirator use.

A feature that was significant was the high inspiratory and expiratory resistances exhibited by the Kemira respirator at relatively low flow rates (2 - 10 l/min). In addition, the results supported earlier work by Louhevaara (1984) that inspiratory resistances are higher than expiratory resistances for this respirator. It would have been expected that the airflows and resistances in the respirator (Kemira) at these low flow rates in the laboratory studies (Chapters 4,5 and 6) would have had an effect on resting physiological values.

In considering the reported reasons for respirator non-use and how these factors may be adequately controlled in order to increase the likelihood of respirator use, evidence from the field studies (Chapters 2 and 7) in this thesis suggested that although airflow resistances were tolerated by respirator users, the goal for designers to reduce the inspiratory and expiratory resistances of respirators still further can be supported from the psycho-physiological evidence of the present study (Chapters 4, 5 and 6).

The present study (Chapters 2 and 3) also identified other key physical characteristics that are related to facemask construction that are critical to respirator tolerance. The weights of the devices, the reaction of the facemask on the skin (irritation and thermal effects) and the comfort of the mask restraints (strap pressure) are all areas where

advances in materials and technology can play a significant role in improving respirator comfort. It is my belief that further research effort should be considered in these areas in respect of respirator design.

The implication of the findings of the present study suggest that even with the acceptable (as defined in the Australian Standard), low and narrow range of inspiratory and expiratory resistances (Chapter 3), linked to the relatively low levels of external work undertaken when required to wear the respirator ( $11.4 \pm 5.8$  %HRR, Chapter 7), respirator users have been shown to still remove the devices (Chapter 2). This finding is significant in an industrial context, where poor respirator cleaning and maintenance practices are likely to exist and where the build up of contaminant in the filtering medium may be a major cause of inspiratory resistance. Psycho-physiological measures (Chapters 4 and 5) appear to be significant contributing factors to respirator tolerance. Significant ( $P < 0.05$ ) increases in perceptions of exertion and difficulty breathing were recorded in the laboratory studies. The results support earlier work (Epstein *et al*, 1982; Morgan, 1983; Morgan and Raven, 1985; Manninen *et al*, 1988; Shimozaki *et al*, 1988; Harber *et al*, 1989; White *et al*, 1989; Wilson *et al*, 1989; Jette *et al*, 1990; Harber *et al*, 1991) who detected changes in the perceptions of respirator users when environmental influences of the respirator were modified by variations in temperature, humidity and air-flow resistance.

## 8.6 Implications for Respirator Design and Manufacture

Although evidence from the present study demonstrated that respirators have little or no effect on minute ventilation, reducing the external dead space of facemasks and reducing weights of the devices may be seen as valuable factors in improving respirator use (Chapter 2).

The material used in facemask construction may be an important influence on respirator acceptability, particularly in reducing the thermal stress imposed by the facemask and the irritation caused on the skin (Chapters 2, 4, 5 and 6). The increasing use of silicone materials in facemask construction, which has been proven



to have superior heat conducting capabilities (DuBois *et al*, 1991), is an important development. Further research into new materials for use in respirator manufacture might be worth consideration.

Evidence from this thesis suggests that further research would be useful on the construction and configuration of inspiratory and in particular, expiratory valve systems, as expiratory resistances have been suggested as the most important resistance variable in respirator acceptability (Raven *et al*, 1979; Louhevaara, 1984). The ability of the valve system to effectively and rapidly remove exhaled air from the facemask appears a critical feature of respirator design. The awareness of individual breathing patterns in many respirator users is an important factor in respirator acceptability (Chapters 2, 4, 5 and 6).

Improving the sensory (vision) and communication difficulties experienced by respirator users is another area for respirator design research (Chapter 2). The psychophysiological, perceptual and psychosocial influences on respirator wearer acceptability have been found to be considerable (Chapters 2, 4, 5 and 6).

There appears to be a considerable lack of training and education in the selection, use and maintenance of respiratory protective equipment (Chapter 2). Many respirator users have inadequate knowledge of airborne hazards and how to protect themselves adequately from these hazards (Chapter 2). Even when comprehensive training and education programmes exist, it has been shown (Chapter 2) that non-use of respirators is still prevalent. Further research is required on the evaluation of successful respiratory protection programmes in order to determine the factors important in user compliance.

## 8.7 Summary

Table 8.4 summarises the results from the experimental and field studies of the thesis and relates these findings to results reported in the literature.

**Table 8.4. Summary of the Physiological Consequences of Respirator Use at Sub-maximal Workloads from the literature and from the experimental studies of the thesis.** (+ + : strong increase, + :increase, =/+ :no difference or slight increase, = :no difference. =/- :no difference or slight decrease, - :decrease, - - :strong decrease).

Physiologic Variable	Result from Literature Review	Chapter 4	Chapter 5	Chapter 6	Chapter 7
Heart Rate	+ or =	=/+	=	=/+	=/+
$\dot{V}O_2$	=/+	=			
$\dot{V}CO_2$	=/-	=/+			
R	=	=			
$\dot{V}_{min}$	=/-,=,+	=			
PDB	++	++			
RPE	=/+ /++		++		
Tskin(lip)	++			++	++
Tskin (cheek)	=,=/+			=/+	=/+

- $\dot{V}O_2$  Oxygen consumption.
- $\dot{V}CO_2$  Carbon dioxide production.
- R Respiratory exchange ratio.
- $\dot{V}_{min}$  Minute ventilation.
- PDB Perceived difficulty breathing.
- RPE Rated perceived exertion.
- Tskin(lip) Skin temperature of lip under the respirator facemask.
- Tskin(cheek) Skin temperature of the cheek adjacent to the ear.

A variety of physical, physiological, psycho-physiological and psychosocial factors influence the use and non-use of respiratory protective devices. This thesis has identified a number of important reasons for non-use cited by respirator users. It has also described the physical characteristics of the equipment commonly used in New Zealand industry, in terms of respirator air-flow resistances (0.01-0.23 kPa/l/sec), weight (12-355 gm) and external dead space (150-229 ml). In assessing the physiological costs of wearing the devices, the thesis compared results of laboratory and field studies in an attempt to identify those physiological parameters that exhibit significant changes that result from respirator use. Measures of physiological strain (heart rate) was demonstrated to be unaltered during respirator use in normal configurations, but significantly effected when inspiratory resistance was artificially increased (Table 8.4). In addition, two psycho-physiological measures were also shown to be effected by respirator use; perceived difficulty breathing, as described by Morgan and Raven (1985); and rated perceived exertion as defined by Borg (1962). The incongruence between the physiological responses to respirator use and the subjective or psycho-physiological responses were clearly demonstrated (Table 8.4). The present study has provided much new information relating to the consequences of respirator use and reasons for non-use. It is hoped this study may in some way, contribute to an improved understanding of the complex nature of respiratory protective practice in New Zealand.

## CHAPTER 9

### 9.0 CONCLUSIONS

The principal aim of this thesis was to define the physiological consequences of wearing an air-purifying respirator and to determine the influence these have on the acceptability of such devices. This was accomplished by undertaking four discrete, but inherently linked approaches of research. The first was a cross sectional survey of respirator use and non-use in a section of New Zealand industry (Chapter 2). Evidence from two surveys, one in Palmerston North and the other in the South Island, indicated that respirator non-use was in fact quite common among the industries surveyed, with well over 50% of users in both surveys not wearing or removing the device for a variety of reasons. Difficulty in breathing, thermal discomfort, difficulty in communication, difficulty in seeing, difficulty in moving and doing the job were all important reasons reported for non-use. It was also evident that little information was provided to respirator users on selection, use and maintenance of the devices. In addition, virtually none of the respondents had undergone any form of medical or physiological assessment prior to the respirator being issued to them.

A significant proportion (20% P.N., 42% S.I.) of respirator users are required to wear the protection in excess of 4 hours per work shift. It was evident that the respirator user attempts to tolerate, as much as possible, the annoying and uncomfortable consequences of respirator use and in doing so may even alter or modify work practices and schedules.

The respirator is a complex device and factors which influence respirator non-use are a combination of physical, physiological and psychological parameters and perceptions.

The second avenue of investigation dealt with primarily respirator air-flow resistance (Chapter 3). The air-flow resistances exhibited by a range of commonly used air-

purifying respirators in New Zealand have been found to be relatively low, when compared to international standards of breathing resistance. The pressures and resistances determined by these studies are comparable if slightly lower, than evaluations undertaken by previous authors (Stemler and Craig, 1977; Louhevaara, 1984), possibly indicating some improvement in design and function of respirators over the intervening years.

Resistances for a range of respirators were evaluated by using continuous and reciprocating flows. Values recorded using continuous flows were compared directly with earlier research (e.g. Louhevaara, 1984) and also with the international standards. No comparable data however, could be found using reciprocating flows. Many cartridge type respirators exhibited comparable low resistances to disposable dust-mask type varieties of respirator. At higher flow rates with the cartridge type respirators, inspiratory resistances could be differentiated between those devices with single and twin cartridges (single cartridge devices having a higher resistance than those with twin cartridges) and expiratory resistances could differentiate those respirators with a single, as opposed to twin exhalation valves. The data from this section also suggested that inspiratory air-flow resistances inside the respirator mask were very much determined by the constituents of the filter material in the cartridge, the number and configuration of cartridges and the nature of the inspiratory valve or orifice. Expiratory resistances inside the mask appeared to be determined by the number, position and properties of the exhalation valves.

The third avenue of study involved the determination of the physiological consequences of respirator use on individuals. Studies were undertaken (Chapter 4) that provided evidence that at rest ( $5-10\% \dot{V}_{O_{2max}}$ ) the respirator imposed no detectable physiological strain in terms of heart rate, oxygen consumption, carbon dioxide production and minute ventilation within the limits of accuracy of the measurement equipment employed. This is in contrast however, to mean heart rate values, which were significantly elevated by respirator use when a pooled analysis of variance technique was utilised. At moderate to high levels of external work ( $25-64\% \dot{V}_{O_{2max}}$ ) however, additional strain was detected in five of the twelve subjects. The overriding

and most common response was the increased perception of difficulty in breathing. Given the inspiratory and expiratory resistances of the device used (Kemira Silner 12), coupled with the variable physiological responses to the moderate levels of exercise, this section provided evidence that psycho-physiological sensations were the factors most likely to cause or predominate feelings of distress or discomfort in individuals required to wear respiratory protection, particularly for extended lengths of time.

The study demonstrated an incongruence between physiological and psycho-physiological consequences of respirator use. The incongruence was illustrated with data that indicated significant increases in rated perceived exertion and perceived difficulty breathing due to respirator use without corresponding variations in the key physiological variables.

The third and fourth areas of investigation also identified the factor that could be considered the most important physiological and psycho-physiological parameter involved in reasons of respirator non-use; thermal discomfort related to an increase in facial skin temperature. Both laboratory (Chapters 5 and 6) and field studies (Chapter 7), found significant increases in facial skin temperatures (lip) under the respirator face mask when subjects were working submaximally, during exercise or work activities. Even though the magnitude of the temperature increase was not large, 1.5°C mean increase in the laboratory study and 2.3°C increase in the field study, the results provide evidence that this is a measurable, perceptual sensation of discomfort, linked with perceptions of difficulty breathing and increased exertion, may be the predominant cues that influence reasons for respirator use or non-use in individuals required to wear them. The implications for respirator design suggest increased and continued research into improved configurations of respirator filters and valves to improve air-flow resistances still further; decreases in weights and dead space volumes of the devices to decrease the potential for cardiorespiratory strain; linked with efforts to utilise materials that will reduce the thermal load imposed by the mask itself.

A conclusion that became apparent to the researcher in the completion of this thesis, was the overriding requirement in any research involving the inter-relation of people

and equipment is to be aware of and utilise the thoughts, perceptions and feelings of the users of the equipment. Whilst this is a fundamental principle in the discipline of ergonomics, its relevance to 'objective' measures in physiological science appeared initially to me as subsidiary. Physiology is very much concerned with delineations of 'central' versus 'local' factors for many biological systems and functions. When other subordinal mechanisms are involved in behaviour, apart from these factors, the incongruence that results is hard to comprehend.

As one eminent Oxford medical scientist noted:-

"...we know a great deal about the atomic structure and physical properties of water,..but we still do not know why it feels wet!".

The present study has taught me a great deal about the structure, physical properties, physiological consequences and psychological influences of respiratory protective devices. I still do not know why they are unacceptable and why individuals at risk choose not to wear them. It is hoped a similar multidisciplinary approach to the problem in the future may provide more substantive answers.

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**APPENDIX 1****Questionnaire Used in the Respirator Usage Survey**

A covering letter preceded the questionnaire which outlined the aims of the survey and emphasised the importance of the co-operation of the subjects in completing the questionnaire. After the preliminary subject identification data, the questions were concerned with the hazards the subjects were exposed to, the type of respiratory protection worn, the reasons for use and non-use and the extent and nature of training and information provided about respirator use.



**MASSEY  
UNIVERSITY**

Palmerston North  
New Zealand  
Telephone (063) 69-099

**FACULTY OF  
BUSINESS STUDIES**

DEPARTMENT OF  
MANAGEMENT  
SYSTEMS

## **RESPIRATOR USAGE SURVEY I**

The use of respirators at work is becoming increasingly more common in N.Z industry. Because of the importance of this type of protection against airborne hazards, this survey is being conducted to identify, (a) the most common hazards workers are exposed to, (b) the types of respirators worn and (c) the reasons for using or not using them.

The success of this survey depends upon your interest and cooperation in providing some of the important information asked in the attached questionnaire. I hope you will be able to complete the questionnaire in your next available moment, (it should only take a few minutes to complete).

Please feel free to air your personal feelings. I can assure you that the survey is CONFIDENTIAL, and will be used only by Massey University researchers.

You will help us greatly by returning the completed questionnaire to us in the enclosed free post envelope. But, if you decide not to complete the questionnaire, we would appreciate you returning it anyway.

With your approval, we would like an opportunity of contacting you again, at a later stage, to enable us to assess any changes in your work environment since this survey.

Thank you for your help.

Yours sincerely

**IAN S LAIRD  
LECTURER  
SAFETY AND OCCUPATIONAL HEALTH**

**CONFIDENTIAL**

## RESPIRATOR USAGE SURVEY

[...]  
1-4

You will be asked a number of questions about using respirators at work. Please complete this questionnaire if you currently use a respirator at some time in your work.

Please answer **all** or the questions unless otherwise directed.

Please use either ticks [✓] when answering, or write clearly in the spaces provided.

The information you provide in this questionnaire will be confidential, and used only by Massey University researchers. However, as we may wish to contact you again at a later time, could you please provide your name, your employers' name and address, as indicated.

## THANK YOU FOR PARTICIPATING

**Office  
Use  
ONLY**

NAME : .....

**EMPLOYER:** .....

ADDRESS : .....

[illegible]

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 104

(Please Tick)

SEX : MALE [ ]  
FEMALE [ ]

[ ]  
5

**AGE :** ..... (Yrs)(at last birthday)

[ . ]  
6-7

(Please Tick)

<b>ETHNIC ORIGIN:</b>	Non-Maori (Caucasian)	[	]
	Maori	[	]
	Pacific Islander	[	]
	Asian	[	]
	Other: (Please Specify)	[	]

[ . ]  
8-9

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 104

**SMOKING:** Do you smoke? Yes [ ]  
No [ ]

[ ]  
10

1. What respiratory hazards are you exposed to at work?

(Tick more than one if applicable)

Dusts	(Solid particles)	[ ]	[ . ] 11-12
Vapours/Mists	(Liquid particles)	[ ]	[ . ] 13-14
Gases/Fumes	(Gas in the Air)	[ ]	[ . ] 15-16
Other (Please Specify)		[ ]	[ . ] 17-18
			[ . ] 19-20

2. Of the above hazards, which do you usually wear a respirator for protection against?

(Tick only one, if possible)

Dusts	(Solid Particles)	[ ]	[ . ] 21-22
Vapours/Mists	(Liquid Particles)	[ ]	[ . ] 23-24
Gases/Fumes	(Gas in the Air)	[ ]	
Other (Please Specify)		[ ]	

3. Why, or for what reason(s) do you wear a respirator?

(Please Tick)

Must wear it to do the work	[ ]	[ . ] 25-26
Wear it as a precaution	[ ]	[ . ] 27-28
Not sure	[ ]	[ . ] 29-30
Other reason(s) (Please Specify)	[ ]	

4a. What do you know about the respiratory hazards you're exposed to (i.e. how does it affect your health)?

	[ . ] 31-32
	[ . ] 33-34

4b. Is the hazard you're exposed to:-

(Please Tick)

Hazardous over a short period of exposure? (Hrs, Days)	[     ]	[     ]
Hazardous over a long period of exposure? (Months, Yrs)	[     ]	35
Note sure?	[     ]	

5. Which type of respirator(s) do you most commonly use?

(Please Tick)

1. Air-purifying type		
a) With cartridge or canister	[     ]	[ . ]
b) Disposable face mask	[     ]	36-37
c) Other (Please Specify)	[     ]	[ . ]
		38-39

.....

2. Supplied Air Type (Airline)	[     ]	
(With hose to air supply)		
3. Self-Contained Breathing	[     ]	
Apparatus (SCBA)		

6a. What is the make or brandname? (Please Specify)

.....	[ . ]
	40-41

6b. Is it a particular model or does it have a code number?  
(Please Specify)

.....	[ . ]
	42-43

7a. Describe what the work you undertake when you wear a respirator?  
(Please give exact description)

.....	[ . ]
	44-45

.....	[ . ]
	46-47

.....

- 7b. Do you regard the work you undertake when wearing a respirator as physically:

(Please Tick)

Very Hard	[     ]
Hard	[     ]
Moderate	[     ]
Light	[     ]
Very Light	[     ]

[   ]  
48

- 8a. How many days per week do you wear a respirator?

(Please Tick)

Daily	[     ]
3 or 4 times per week	[     ]
1 or 2 times per week	[     ]
less than once a week	[     ]

[   ]  
49

- 8b. How many days per week should you wear a respirator?

(Please Tick)

Daily	[     ]
3 or 4 times per week	[     ]
1 or 2 times per week	[     ]
less than once a week	[     ]

[   ]  
50

9. What is the longest time you wear a respirator for each day/shift?

(Please Tick)

Less than 15 minutes	[     ]
Between 15 minutes and 30 minutes	[     ]
Between 30 minutes and 1 hour	[     ]
Between 1 hour and 4 hours	[     ]
Over 4 hours	[     ]

[   ]  
51

10. Do you ever take the respirator off, for some reason, before the work is finished?

(Please Tick)

a) Always wear a respirator	[     ]	If you ticked a) <b><u>Go to Question 11</u></b>
b) Sometimes take the respirator off	[     ]	If you ticked
c) Frequently take the respirator off	[     ]	b), c) or d)
d) Hardly ever use the respirator	[     ]	<b><u>Go to Question 12.</u></b>

[   ]  
52

11. What are/were the reasons for you always wearing the respirator?  
(Please Specify)

.....

.....

.....

[ . ]  
53-54

[ . ]  
55-56

(Please Goto Question 13 if you answered Question 11)

12. What are/were the reasons for not using, or taking off the respirator?

(Tick more than one if desired)

Too hot	[     ]
Too heavy	[     ]
Too tight	[     ]
Difficulty seeing	[     ]
Difficulty breathing	[     ]
Difficulty moving	[     ]
Difficulty doing the job	[     ]
Felt awkward or clumsy	[     ]
Felt self-conscious	[     ]

Other reason(s):        (Please Specify)

.....

.....

.....

.....

.....

[ . ]  
57-58

[ . ]  
59-60

13a).Do you think respirators are generally good things?

(Please Tick)

Yes	[     ]
No	[     ]

[     ]  
61

13b).What do you find good about your respirator?  
(Please Specify)

[ . ]  
62-63

.....

.....

.....

[ . ]  
64-65

14. Do you have any other comments or suggestions about wearing the  
respirator? (Please Specify)

.....

.....

.....

[ . ]  
66-67

[ . ]  
68-69

15a).Did you receive any training or advice about using and/or fitting the  
respirator properly?

Yes	[     ]	If you ticked, Go to Question 15b)
No	[     ]	If you ticked, Go to Question 16a)

[     ]  
70

15b).What, briefly were you told (main points)?  
(Please Specify)

.....

.....

.....

[ . ]  
71-72

[ . ]  
73-74

[ . ]  
75-76

15c).By whom were you told? (Please Specify)

.....

[ . ]  
77-78



**16a).Did you receive advice or information about maintaining the respirator? (i.e. cleaning, checking, replacing canisters etc)?**

**Yes**      [      ]      **If you ticked, Go to Question 16b)**

No                    [                    ]                    If you ticked, Go to Question 17a)

[ ]  
79

**16b).What briefly were you told (i.e. main points)?**  
(Please Specify)

[ ]  
80

[ . ]  
1.2  
Card 2

**17a).Before providing you with the respirator, did anyone ask about your past medical history, or give you a medical examination?**

(Please Tick)

Yes ☐ Goto Question 17b)

No [ ]

$$\begin{bmatrix} & \\ & \\ 3 & \end{bmatrix}$$

**17b).If you answered YES, what were you asked, and/or what was the extent of the medical examination? (Please detail).**

[ . ]  
4 - 3

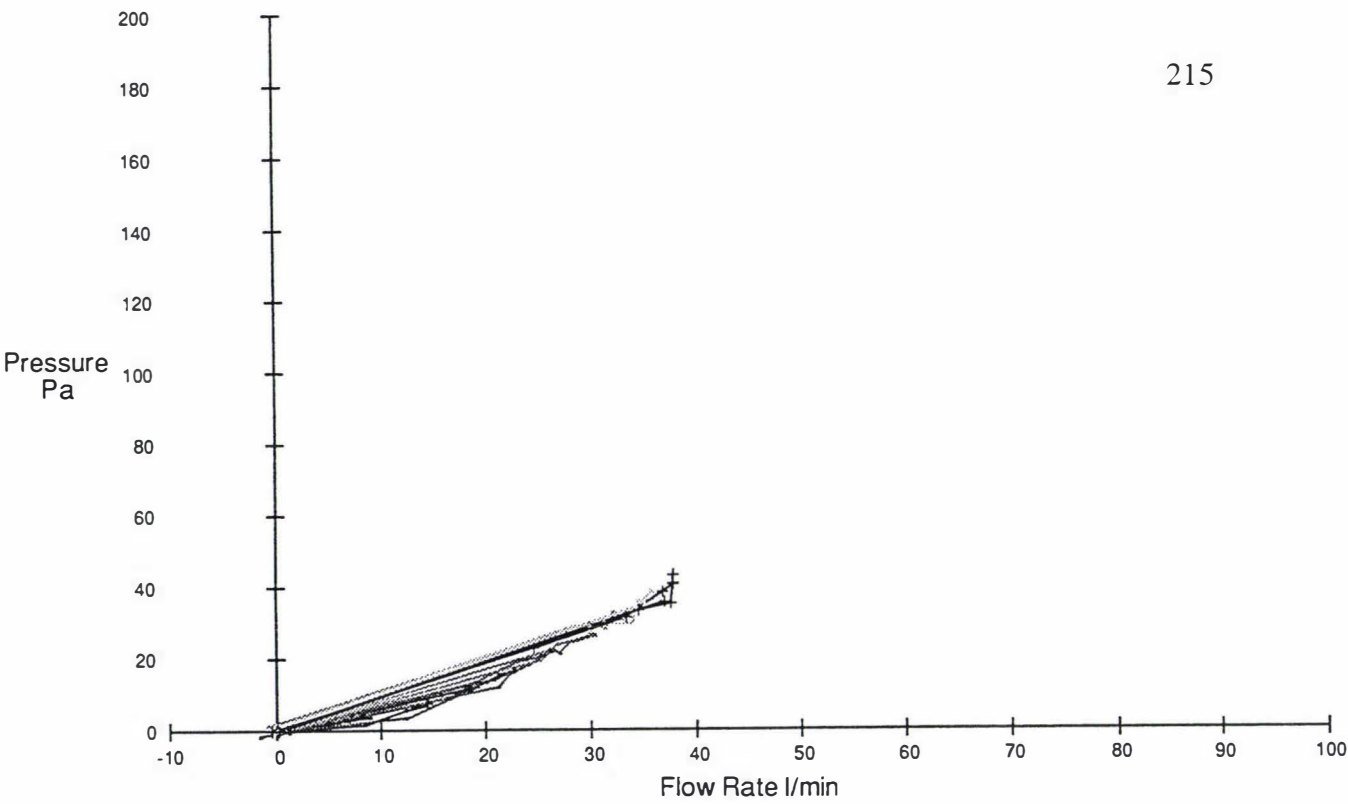
[ . ]  
6-7

Many thanks for your time and co-operation  
in filling out this questionnaire.

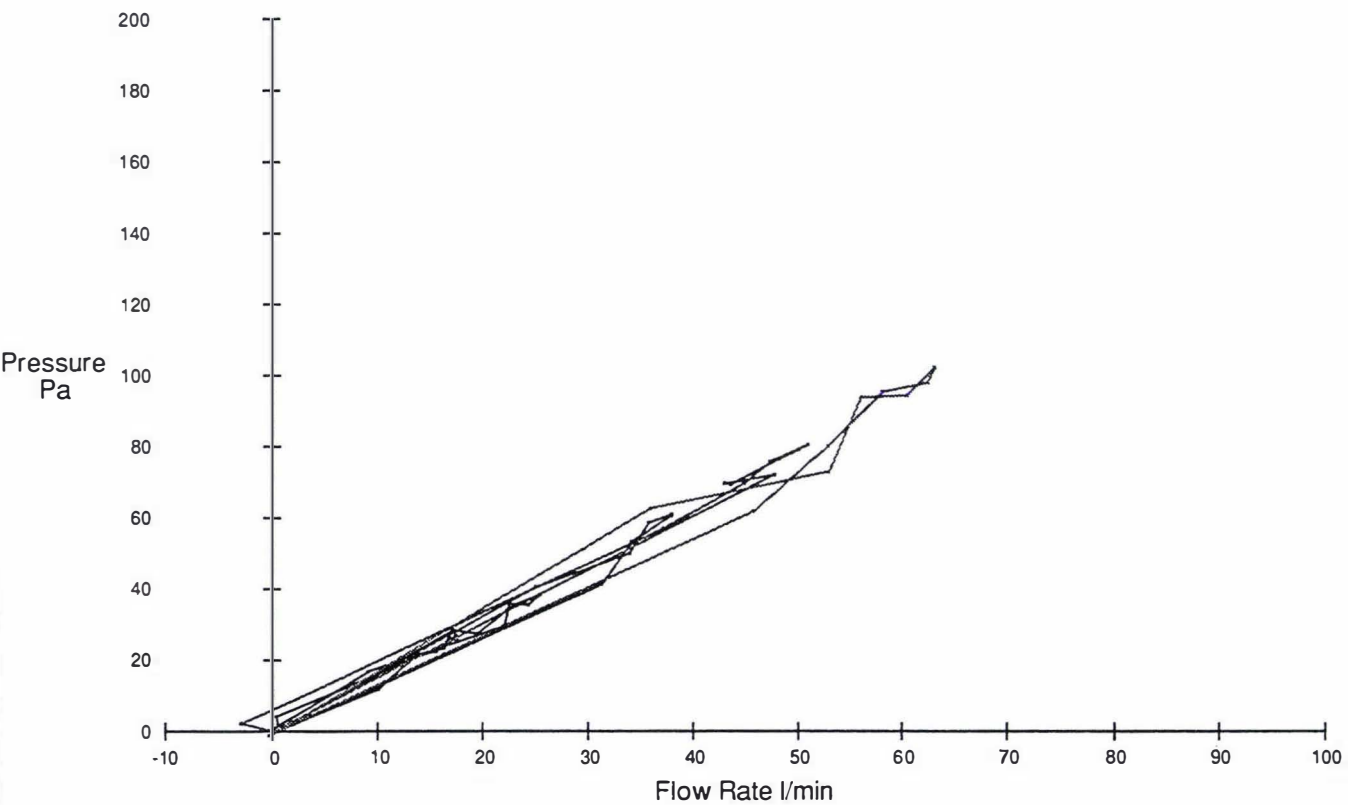
## APPENDIX 2

### **Pressure - Flow Curves for the Eight Respirators Evaluated**

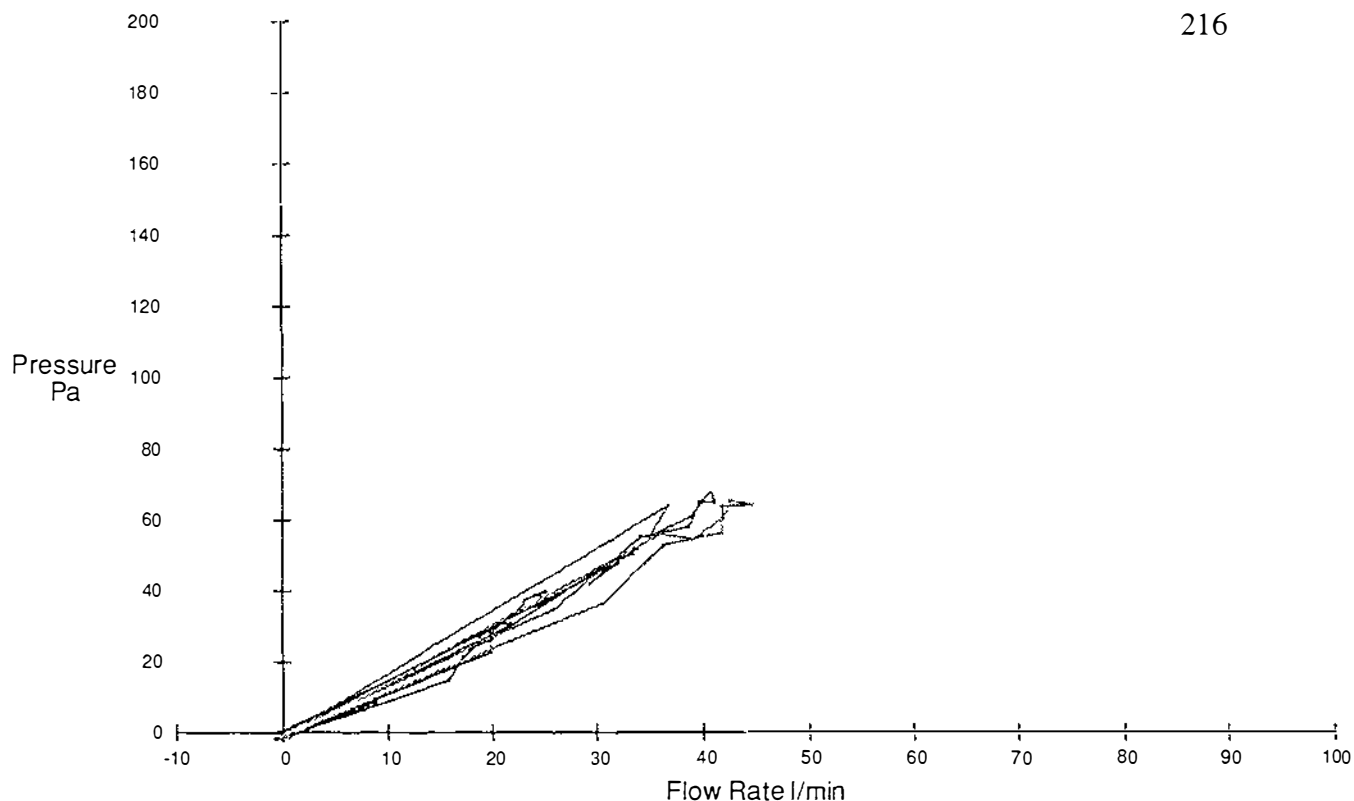
The following figures are the pressure-flow charts obtained from the evaluations of the eight respirators in Chapter 3. The first three figures (A 2.1 - 2.3) relate to the dust mask type respirators (3M 9900, 3M 9920 and Moldex 3400). The remaining figures (A 2.4 - 2.8) are for the cartridge type air-purifying respirators (Sundstrom SR 90, Norton 7700, Protector (two) and Kemira Silner 12).



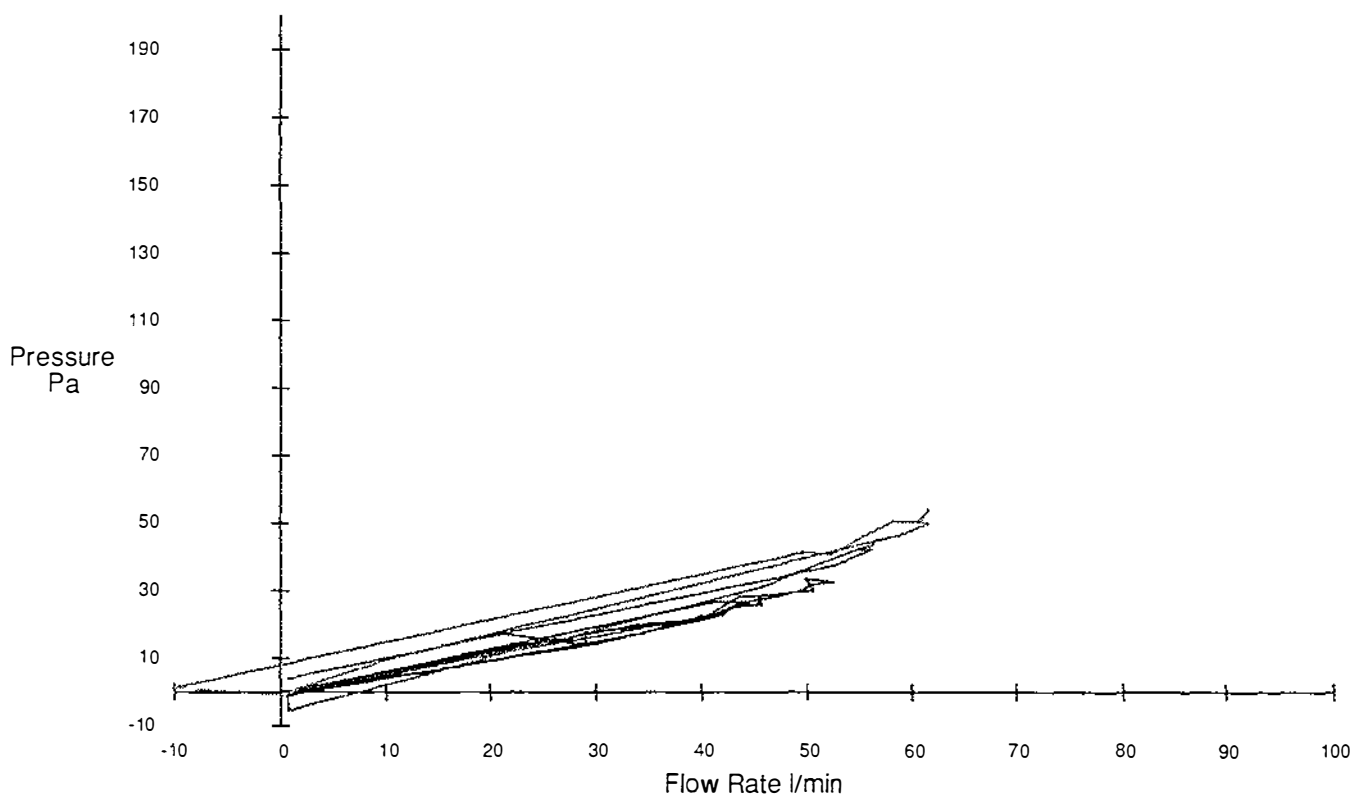
**Figure. A 2.1 Pressure-low curves for the 3M #9900 respirator.**



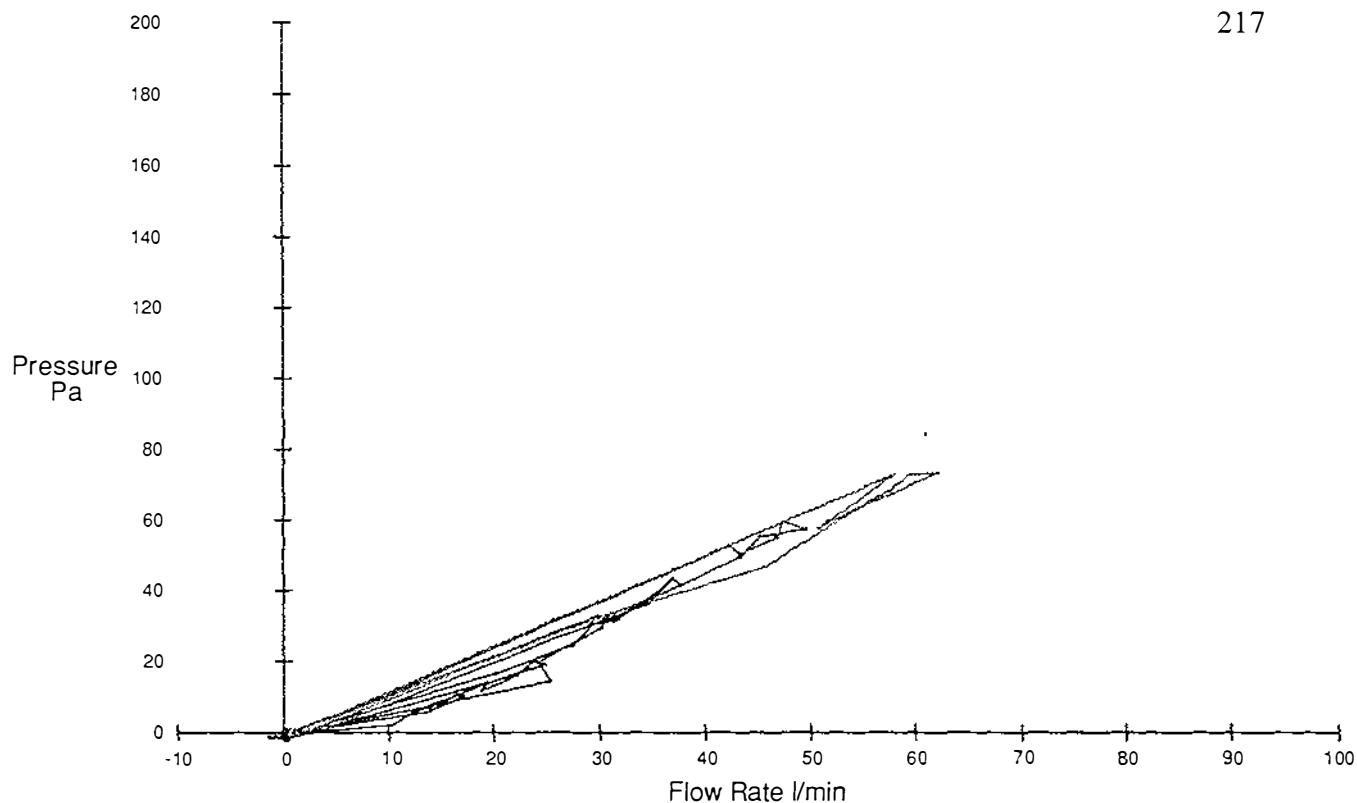
**Figure A 2.2. Pressure-flow curves for the 3M #9920 respirator.**



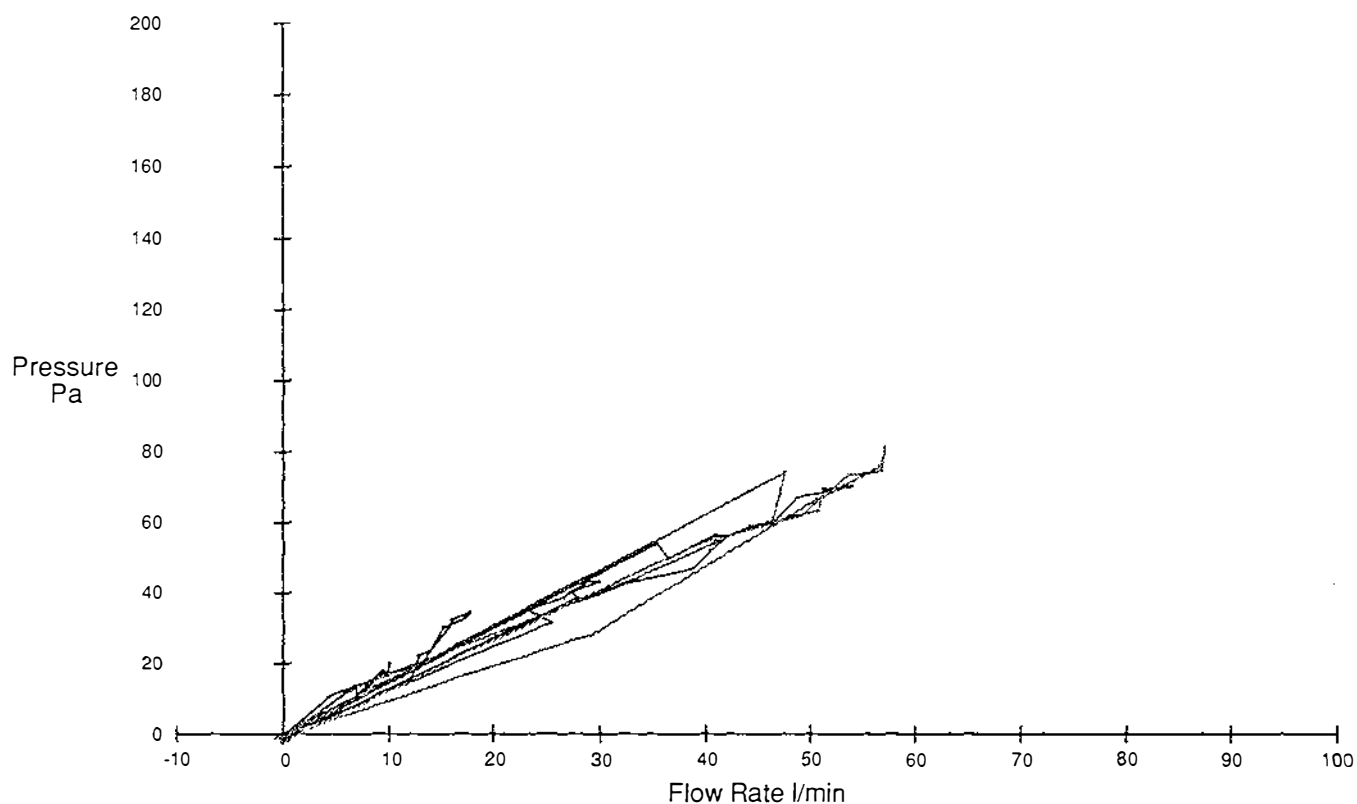
**Figure. A 2.3 Pressure-flow curves for the Moldex #3400 respirator.**



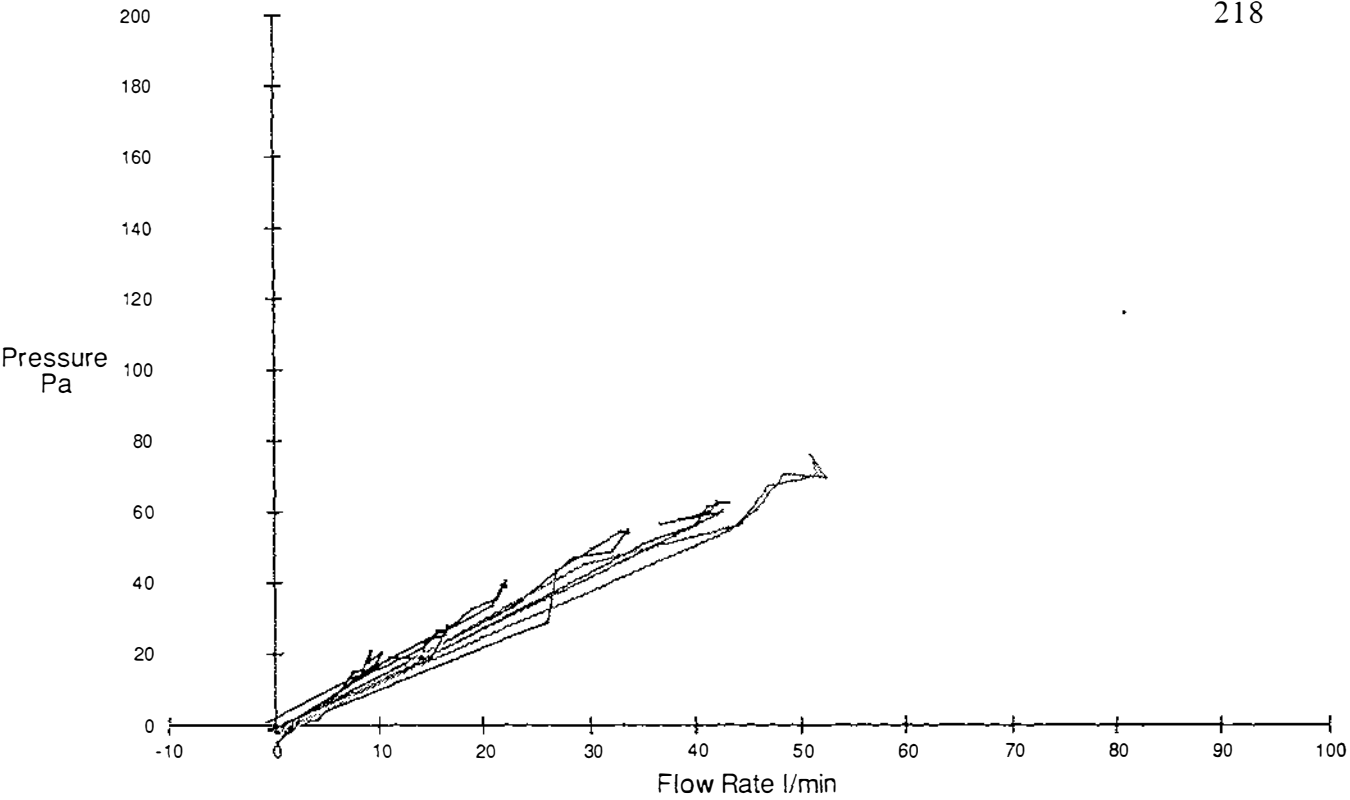
**Figure A 2.4. Pressure-flow curves for the Sundstrom SR 90 respirator.**



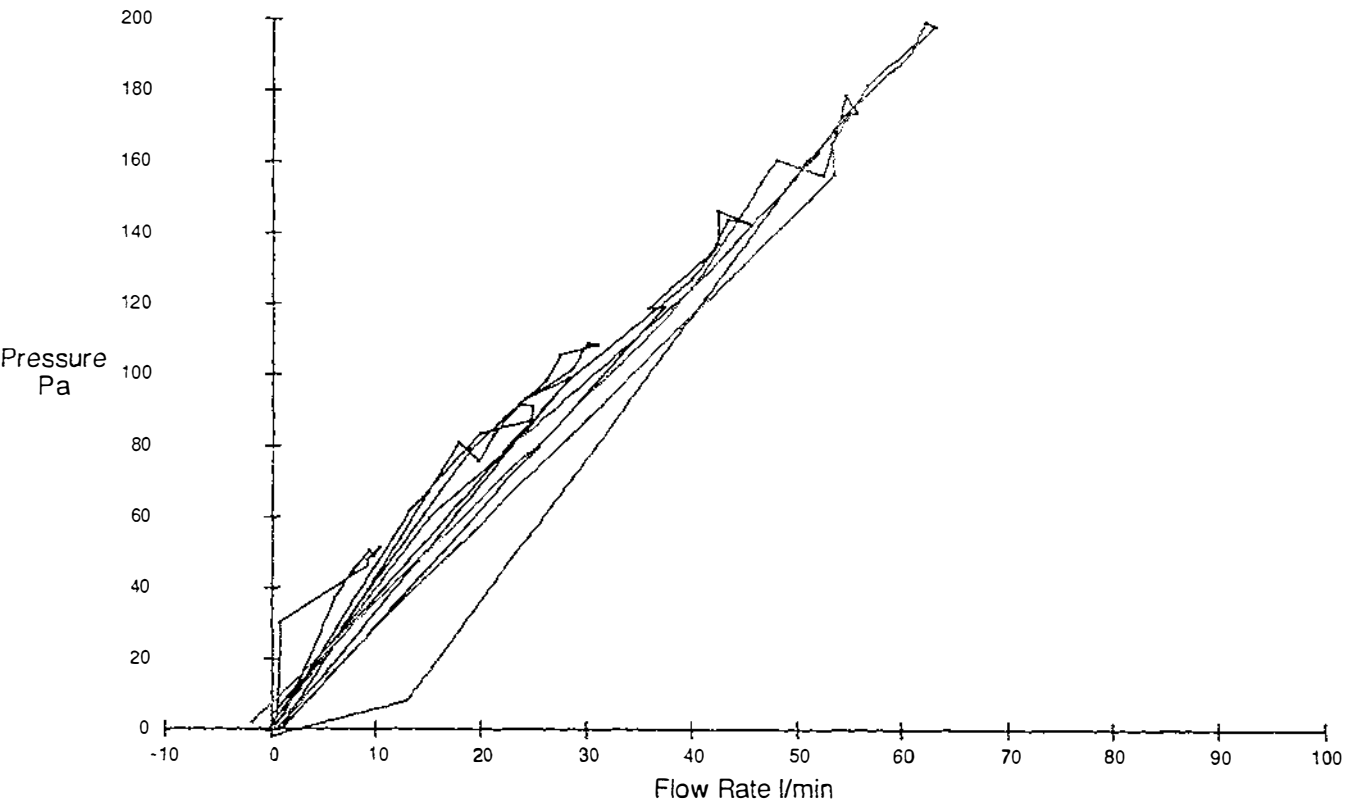
**Figure. A 2.5 Pressure-flow curves for the Norton #7700 respirator.**



**Figure A 2.6. Pressure-flow curves for the Protector (twin cartridge) respirator.**



**Figure. A 2.7 Pressure-flow curves for the Protector (single cartridge) respirator.**



**Figure A 2.8. Pressure-flow curves for the Kemira Silner 12 respirator.**

## APPENDIX 3

### Description of the Ergolab 2 Programme

#### 1.0 DOCUMENTATION

##### 1.1 Program Objective

The objective of the Ergolab2 programme was to provide a software interface with real time capability which linked a variety of hardware devices together to allow efficient and accurate data capture.

##### 1.2 Operation

This was achieved by the use of Borland Turbo C programming language (Turbo Pascal Version 6.0, 1983, 90 Borland International, USA), VP Planner (Paperback Software Int, USA, 1987) spreadsheet compatibility and Microsoft Chart as software utilities. The hardware requirements included an IBM compatible PC with graphics card (Harvard Graphics) with ansi.sys loaded and a 40 MB hard drive.

The computer is connected to the following measurement equipment: Monark Ergomedic 818 cycle ergometer, heart rate monitor, Datex Normocap oxygen/carbon dioxide analyser, a dry gas volume meter. The devices are connected via an 8255 input/output (I/O) programmable card with 48 I/O lines and 3 independent 16 bit counters, each with a count rate of up to 2 MHz, which in turn is connected to an ADDA-12 analog-digital/ digital-analog card. Ergolab2 was able to read data directly from the cards, processed the data, undertook calculations and displayed the data in a variety of screen layouts for data monitoring. The data files produced were stored directly onto data disks for subsequent analysis and graphics display.

##### 1.3 Description of the Process.

Data was generated from the Program Ergo Lab and written to a data file with a filename of (e.g. 001.dat). A duplicate copy of the worksheet template (copyme.wks) was generated a 001.wks and from this spreadsheet file analysis was able to be carried out. The duplication was made for each data file because of the file structure.

The following was the sequence of events that generated the worksheet.

Ergo Lab program ----> Run the experiment ----> Produce a data file e.g.  
001.dat

Spreadsheet analysis 001.dat 001.wks

[illegible]

--- Analysis ---

11

Save the results ----> 001.wks

## 1.4 File Description

Master.wks

this file was a master template file and was write protected. The file was for development purposes and was not be used for analysis of data. As a consequence of the write protect facility any modification of the master template file would fail.

Copyme.wks

this file was a working template which was copied to produce analysis files by using the DOS command copy.

E.g. from a DOS prompt carry out the following command -

copy copyme.wks 001.wks

### 1.5 Use of the Spreadsheet.

Note: All cells within the spreadsheet were locked for protection against accidental modification.



1. Load VP Planner Plus from the menu or DOS
2. Setup the directory path to find the data & spreadsheet files  
     /f (ile)  
         d (irectory)  
         Enter path: e.g. c:\vppdata  
         [Return]
3. Load the Spreadsheet analysis file.  
     /f (ile)  
         r (etrieve)  
         select file from the list  
         [Return]
4. Load in the data from the data file.  
     Move the cursor to cell location A1 -          the cursor must be in this location.  
     Press the [Home] key  
     Load the data file e.g. 003.dat  
     /f (ile)  
         i (mport)  
         n (umbers)  
         enter the filename e.g. 003.dat  
         [Return]
5. Locate the cursor at position A200  
     Press the function key [F5]  
         A200  
         [Return]

The following were Printing and Graphing commands.

1. Print results (e.g. for 4 bags of data)  
     /p (rint)  
         p (rinter)  
         r (ange)  
         A200..S218  
         g (o)

q (uit)

2. Graph (E.g. Heart rate by Worklevel)

The first graph has by default being setup to allow for four (4) bags.

/g (raph)

v (iew)

If the number of bags is required to be increased.

/g (raph)

x (measure of Worklevel)

B215..Bxxx (where xxx is the last row with a bag number)

[Return]

a (measure of Heart rate)

J215..Jxxx (where xxx is the last row with a bag number)

[Return]

v (iew)

q (uit)

## APPENDIX 4

### Calibration data for Datex Normocap Gas Analyser.

Calibration of the Datex Normocap gas analyser was undertaken in line with the manufacturers recommendations. On each occasion the gas analyser was preconditioned with a 'warm-up' period before recordings were made. A Douglas bag was used to collect air and measurements were taken by introducing the probe via a one-way valve system. Three or four measurements were taken each day over a period of a week. Percentage oxygen and carbon dioxide concentrations were recorded. Mean, standard deviations and percentage error were able to be calculated (Appendix A4 ).

Appendix A4. Calibration data for Datex gas analyser

TIME	% O2	% CO2	Stats	Error %	O2 Ext %	O2 Ext Stats	Drf Err %
11.55	17.3000	3.6000	17.3000	0.0000	3.5000	3.5000	0.0000
2.00	17.2000	3.6000	+/-	-0.1000	3.6000	+/-	-2.8571
4.00	17.4000	3.7000	0.1000	0.1000	3.4000	0.1000	2.8571
11.55	17.5000	3.1000	17.5000	0.0000	3.3000	3.3000	0.0000
2.00	17.7000	3.2000	+/-	0.2000	3.1000	+/-	6.606
4.00	17.3000	3.1000	0.2000	-0.2000	3.5000	0.2000	-6.0606
12.15	17.8000	3.7000	17.5000	0.3000	3.0000	3.3000	9.0909
1.55	17.4000	3.7000	+/-	-0.1000	3.4000	+/-	-3.0303
4.15	17.4000	3.7000	0.2000	-0.1000	3.4000	0.2000	-3.0303
6.20	17.4000	3.6000	17.7250	-0.1000	3.4000		-3.0303
11.40	17.4000	3.3000	+/-	-0.3250	3.4000	3.0750	-10.5691
1.40	17.9000	3.2000	0.2363	0.1750	2.9000	+/-	5.6911
4.00	17.7000	3.2000		-0.0250	3.1000	0.2363	-0.8130
5.45	17.9000	3.1000	17.9000	0.1750	2.9000		5.6911
3.15	17.9000	3.1000	+/-	0.0000	2.9000	2.9000	0.0000
4.15	17.9000	3.1000	0.0000	0.0000	2.9000	+/-	0.0000
5.00	17.9000	3.1000		0.0000	2.9000	0.0000	0.0000
11.00	17.8000	3.3000	17.8000	0.0000	3.0000	3.0000	0.0000
1.45	17.8000	3.2000	+/-	0.0000	3.0000	+/-	0.0000
3.40	17.8000	3.2000	0.0000	0.0000	3.0000	0.0000	0.0000
4.55	17.8000	3.2000		0.0000	3.0000		0.0000
Mean	17.6286	3.3333	5.914	-0.0000	3.1714	1.1006	-0.0000
+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
S.D.	0.2452	0.2436	8.5188	0.1392	0.2452	1.5192	4.3424

Time

% O2

% CO2

Stats

Error %

O2 Ext %

O2 Ext Stats

Drf Err %

Time of analysis

Percentage oxygen

Percentage carbon dioxide

Statistical values (mean, S.D. standard deviation) for percentages

Percentage error

Amount of oxygen extracted from the air (room air-bag contents)

Statistical parameters for O2 Ext %

Drift as percentage error

**APPENDIX 5**

**Description of the Statistical Analysis in the Analyses of Variance of Experimental Designs with Replicated Latin Squares (R. Munford, 1994).**

## THE EXPECTED VALUES OF MEAN SQUARES IN ANALYSES OF VARIANCE OF EXPERIMENTAL DESIGNS WITH REPLICATED LATIN SQUARES

### Introduction.

In any analysis of variance the expected values of mean squares can be expressed in terms of components of variance that are determined by the mathematical model underlying the analysis. In the particular case of experimental designs with replicated latin squares, the underlying model expresses the observed value for the  $j$ th row and  $k$ th column of the  $h$ th square that has received the  $i$ th treatment:

$$X_{hijk} = \mu + \lambda_h + \tau_i + (\lambda\tau)_{hi} + \rho_{hj} + \chi_{hk} + \varepsilon_{hijk}$$

The ranges of the indices (subscripts) are:

- $h$  from 1 to  $r$  (the number of latin square replicates);
- $i, j, k$  from 1 to  $t$  (the number of treatments, rows or columns, which are the same in a latin square design).

The definitions of the parameters (on the right hand side of the model) are:

- $\mu$  the population mean;
- $\lambda, \tau$  the main effects, latin square replicates and treatment, respectively;
- $(\lambda\tau)$  the interaction, between latin square replicates and treatments;
- $\rho, \chi$  nested effects, rows within squares and columns within squares;
- $\varepsilon$  the error associated with each observation.

The Roman capitals corresponding to the Greek letters in the model are used in tables of analyses of variance to represent the mean squares and identify variance components.

### Fixed and Random Effects.

The numerical estimates of the mean squares in an analysis of variance are not altered by the nature of the main (and nested) effects, but the interpretation of these estimates is affected. In an experimental design with replicated latin squares, the nested effects (Rows within squares and Columns within squares) normally are defined as random.\* On the other hand, the main effects (Latin square replicates and Treatments) may be defined either as random or as fixed.\* The consequences of any assumptions about the nature of these main effects for the interpretation of the results of an analysis of variance can be determined by examining the expected values of the mean squares for all effects and their interactions.† Three possible sets of assumptions about the main effects are examined in the following sections.

\* An effect is defined as fixed if any of the following conditions apply:

All levels of the effect are included in the experiment.

Conclusion will be drawn only with regard to levels of the effect included in the experiment.

The levels of the effect included in the experiment were not chosen randomly, even though the selection may be from an normally distributed population of an infinite number of levels.

An effect is random if the levels in the experiment are a random sample from a normally distributed infinite population of levels.

† Snedecor, GW & Cochran WG (1967). *Statistical Methods*.

Ames, Iowa: Iowa State University Press. 6th edition, pp. 285-289, 312-315, 364-369

## Analysis of Variance

SOURCE OF VARIATION	D. F.	MEAN SQUARE	EXPECTED VALUE (Variance components of mean square)
Latin squares	$n-1$	$L$	$\sigma^2 + t\sigma_R^2 + t\sigma_C^2 + t\sigma_{LT}^2 + t^2\sigma_L^2$
Rows within sqs	$n(t-1)$	$R$	$\sigma^2 + t\sigma_R^2$
Columns within sqs	$n(t-1)$	$C$	$\sigma^2 + t\sigma_C^2$
Treatments	$t-1$	$T$	$\sigma^2 + t\sigma_{LT}^2 - n t \sigma_T^2$
Squares by Treatments	$(n-1)(t-1)$	$LT$	$\sigma^2 + t\sigma_{LT}^2$
Error	$n(t-1)(t-2)$	$E$	$\sigma^2$

## Tests of Significance

An F-test to establish the probability that the mean square for any row in the analysis of variance table represents a real effect is calculated by dividing the mean square in question by another mean square. The appropriate mean square for use as a divisor contains all but the last of the variance components for the mean square being tested. (The null hypothesis is that this last term of the expectation for a mean square is zero.)

With Rows within squares, Columns within squares and the interaction Squares by Treatments, the appropriate denominator for the F-test is the Error mean square. The calculated F-value is compared with the tabular F-value (at a selected level of significance) for  $n(t-1)$  and  $n(t-1)(t-2)$  degrees of freedom, in the case of the nested effects, and for  $(n-1)(t-1)$  and  $n(t-1)(t-2)$  degrees of freedom, in the case of the interaction.

The appropriate denominator for Treatments is the interaction Squares by Treatments mean square. The degrees of freedom used to select the appropriate tabular F-value are  $t-1$  and  $(n-1)(t-1)$ .

With the main effect Latin squares, none of the other mean squares in the table is an appropriate denominator for an exact F-test. A test ratio can be constructed by using a denominator that is a combination of mean squares:

$$\{R\} + \{C\} + \{LT\} - 2\{E\}$$

and the ratio then takes the form:

$$(\{L\} + 2\{E\})/(\{R\} + \{C\} + \{LT\})$$

This is not an F-ratio but the F tables can be used if they are entered with modified degrees of freedom:

$$(\{L\} + 2\{E\})^2 / \{L\}^2 / ((n-1) - 2\{E\}^2 / [n(t-1)(t-2)])$$

and  $(\{R\} + \{C\} + \{LT\})^2 / (\{R\}^2 / (t-1) + \{C\}^2 / (t-1) + \{LT\}^2 / [(n-1)(t-1)])$

Where effects are random, it is often more useful to estimate the numerical value of the population variance for the parameters of the model rather than test whether these variance differ from zero. Since these are estimates based on a sample drawn from the population  $s^2$  is used in place of  $\sigma^2$ . The calculations, starting from the last row of the analysis of variance table, are:

$$s^2 = \{E\}$$

$$s^2_{LT} = (\{LT\} - \{E\})/t$$

$$s^2_T = (\{T\} - \{LT\})/nt$$

$$s^2_R = (\{R\} - \{E\})/t$$

$$s^2_C = (\{C\} - \{E\})/t$$

$$s^2_L = (\{L\} + 2\{E\} - \{R\} - \{C\} - \{LT\})/t^2$$

### Treatments Effect Fixed

#### Analysis of Variance

SOURCE OF VARIATION	D. F.	MEAN SQUARE	EXPECTED VALUE (Variance components of mean square)
Latin squares	$n-1$	$L$	$\sigma^2 + t\sigma_R^2 + t\sigma_C^2 + t^2\sigma_L^2$
Rows within sqs	$n(t-1)$	$R$	$\sigma^2 + t\sigma_R^2$
Columns within sqs	$n(t-1)$	$C$	$\sigma^2 + t\sigma_C^2$
Treatments	$t-1$	$T$	$\sigma^2 + t\sigma_{LT}^2 + nt\sigma_T^2$
Squares by Treatments	$(n-1)(t-1)$	$LT$	$\sigma^2 + t\sigma_{LT}^2$
Error	$n(t-1)(t-2)$	$E$	$\sigma^2$

#### Tests of Significance

The only result of changing Treatments from a random to a fixed effect is the removal of the term for the interaction from the expectation of the Latin squares mean square. It therefore follows that there are no changes in the calculations of F-tests for the other mean squares from those described in the second and third paragraphs on p.2.

With the main effect Latin squares a test ratio is constructed by using a denominator that combines three mean squares:

$$\{R\} + \{C\} - \{E\}$$



The test ratio then takes the form:

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$$(\{L\} + \{E\})/(\{R\} + \{C\})$$

The F tables are entered with modified degrees of freedom:

$$(\{L\} + \{E\})^2 / (\{L\}^2/(n-1) + \{E\}^2/[n(t-1)(t-2)])$$

and  $(\{R\} + \{C\})^2 / (\{R\}^2/[n(t-1)] + \{C\}^2/[n(t-1)])$

## Estimation of Variance Components

Changing Treatments from a random to a fixed effect results in a change, from that on p 3, in the calculation for  $s_L^2$  :

$$s_L^2 = (\{L\} + \{E\} - \{R\} - \{C\})/t^2$$

Although the method of calculation is unchanged,  $s_T^2$  now is related to a population that is restricted by the fixed levels of the Treatment.

## Latin Squares and Treatments Effects Fixed

### Analysis of Variance

SOURCE OF VARIATION	D. F.	MEAN SQUARE	EXPECTED VALUE (Variance components of mean square)
Latin squares	$n-1$	$L$	$\sigma^2 + t \sigma_R^2 + t \sigma_C^2 + t^2 \sigma_L^2$
Rows within sqs	$n(t-1)$	$R$	$\sigma^2 + t \sigma_R^2$
Columns within sqs	$n(t-1)$	$C$	$\sigma^2 + t \sigma_C^2$
Treatments	$t-1$	$T$	$\sigma^2 + n t \sigma_T^2$
Squares by Treatments	$(n-1)(t-1)$	$LT$	$\sigma^2 + t \sigma_{LT}^2$
Error	$n(t-1)(t-2)$	$E$	$\sigma^2$

### Tests of Significance

The only result of changing Latin squares to a fixed effect is the removal of the term for the interaction from the Treatments mean square. The F-test for this mean square now has the same denominator as Rows within squares, Columns within squares, and the interaction (see paragraph two on p 2). The F table is entered with degrees of freedom  $t-1$  and  $n(t-1)(t-2)$ .

The test ratio and degrees of freedom for the Latin squares effect is the same as shown at the top of this page.

With both Latin squares and Treatments fixed, the interaction is now also fixed and the estimated variances for all three relate to a population restricted by the fixed levels of the Treatment and fixed allocation of the replicated Latin squares. The calculation of  $s^2_L$  is the same as shown on p 4 and that of  $s^2_{LT}$  the same as shown on p 3. The calculation of  $s^2_T$  is altered:

$$s^2_T = (\{T\} - \{E\})/nt$$

R E Munford, Dec 1967 (revised Sep 1994)

## APPENDIX 6

### Modifications to the Socially Acceptable Monitoring Device (SAMI)

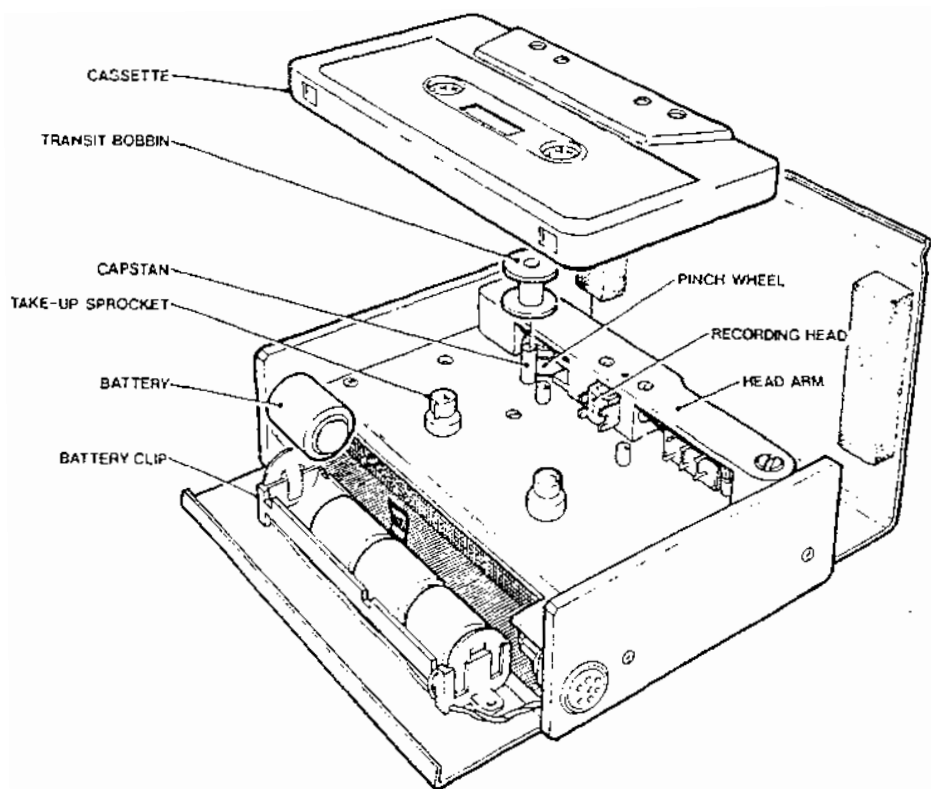
The MEDILOG 4-24 Miniature Analogue Tape Recorder is a self-contained pocket-sized instrumentation tape recorder, designed especially for monitoring bio-electric information for periods of up to 24 hours on mobile subjects. The device is also termed 'SAMI', (Socially Acceptable Monitoring Instrument) and shown in Figures A6.1 and A6.2. The recorder is powered by 4 Mallory RM1N mercury cells, which are inserted in the battery clip as shown in Figure A6.1.

The Medilog recorder was used in conjunction with a playback unit (Oxford PB-2), using C120 tapes replayed at accelerated speed.

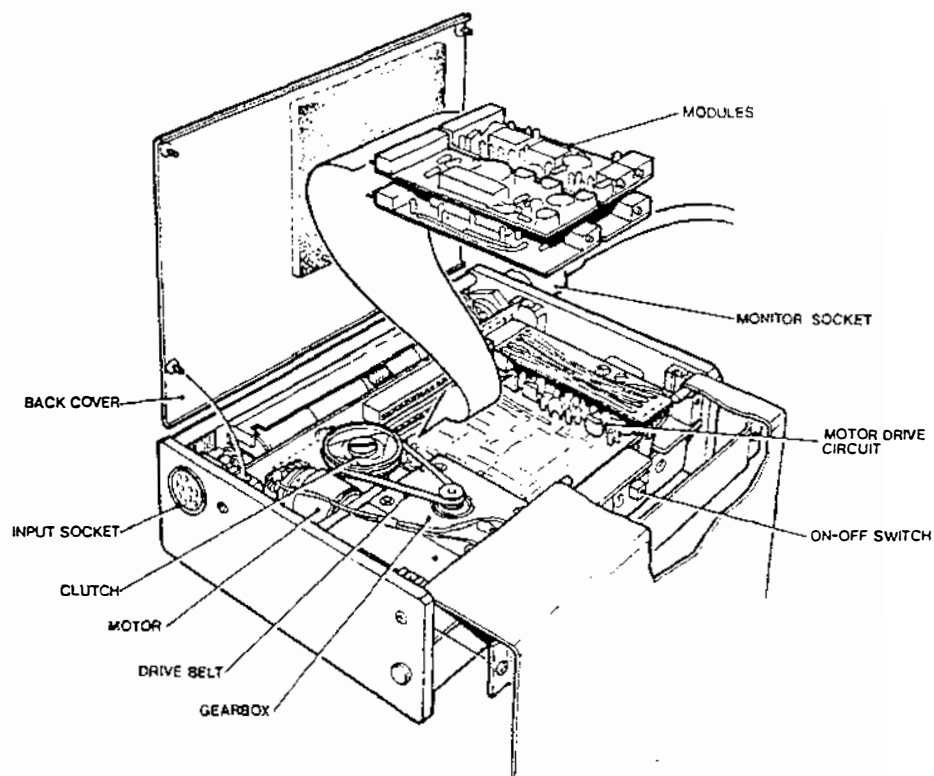
The recorder accepts modular plug-in amplifier and timing modules and can accommodate quick changes of configuration to suit particular requirements.

In this study, a temperature module was installed to measure skin temperatures in two different locations (lip and cheek skin temperatures) using two 15 mm aluminium thermistors. Of the four channels available, Channels 2 (pins C and D) and 3 (pins E and F) were selected for each temperature thermistor. The thermistors were calibrated using a variable temperature water bath, as described in Chapter 7, section 7.2.

Leads were attached to the skin using adhesive tape, and the recorder unit was carried by the subject in a waist mounted carrying case. External leads were tape down to ensure they did not interfere with normal work operations.



**Figure A 6.1. Diagram of cassette position and recording head features of the SAMI.**



**Figure A 6.2. Diagram of motor drive, gearbox and module connection position for SAMI.**

**APPENDIX 7**

**Facial Skin Temperatures and Heart Rate Data of the Twelve Subjects in the Work Environment Study With and Without Wearing a Respirator.**

